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Review on solar powered rotary desiccant wheel cooling system

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ABSTRACT

Rotary desiccant wheel cooling system operates on the principle of adsorption dehumidification and evaporative cooling. The system adopts natural substance as working fluid and can be driven by low grade thermal energy such as solar energy. Due to these merits, solar powered rotary desiccant wheel cooling system has recognized as one of good alternatives to conventional vapor compression air conditioning system and has obtained increasing interests in the past years. This paper aims to summarize recent research developments related to solar powered rotary desiccant wheel cooling system and to provide information for potential application. Based on whether auxiliary refrigeration system is adopted, the systems are divided in to two categories: separate solar powered rotary desiccant wheel cooling systems and hybrid solar powered rotary desiccant wheel cooling systems. Within the first category, separate solar powered rotary desiccant wheel cooling systems are reviewed according to different types of solar collector. It can be found that these researches mainly focus on feasibility study of such system under different climates. Results show that separate solar powered rotary desiccant wheel cooling systems can be adopted in several representative cities in Europe, Asia, Australia and Africa. However, system performance in terms of solar fraction and thermal coefficient of performance varies greatly with respect to different operation conditions. For the second category, works related to hybrid solar powered rotary desiccant wheel cooling systems are grouped by types of auxiliary refrigeration systems. It can be found that vapor compression system is widely adopted in these hybrid systems. Also, due to both solar energy and electricity are consumed in hybrid systems, primary energy consumption is an important performance index. Results show that hybrid solar powered rotary desiccant wheel cooling system can obtain significant energy saving compared with conventional vapor compression system.

Contents

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1. Introduction

Nowadays, there is still a big amount of needs in air conditioning systems with environmental change and improvement of living standards. However, air conditioning systems have already accounted for a large part of energy consumption in the whole society, and then how to effectively increase the energy utilization ratio of air conditioning system is crucial for sustainable development. Traditional air conditioning system operate on vapor compression (VC) cycle, although theoretical COP (coefficient of performance) of the system can reach to about 30, due to the existence of heat transfer difference and other irreversible loss, actual COP only can reach to 3.5. Besides, such systems rely on electricity and the adopted refrigerant still make contributions to greenhouse emission. Rotary desiccant wheel air conditioning system, which operates on the principle of adsorption dehumidification and evaporative cooling, becomes one of the good alternatives to conventional VC systems. In rotary wheel desiccant cooling system, desiccant material (solid adsorbent) is impregnated into rotary desiccant wheel, process air is pumped into desiccant wheel to contact with desiccant material, due to the vapor concentration difference between process air and desiccant material, water vapor within process air can be adsorbed by solid desiccant material, thus latent load of process air is removed and humidity ratio of the air is always extremely low. After that, an evaporative cooling is adopted to handle the sensible load. With use of a dehumidification component and evaporative cooler, comfort air with decreased humidity ratio as well as temperature can be supplied to conditioned space in cooling season. In order to make desiccant material reuse, a regeneration process in which air with high temperature is adopted to desorb water vapor from desiccant material operates in parallel with dehumidification process. On the other hand, if regeneration air is adopted as the supply air to the conditioned space, the system realizes function of heating and humidification for heating season. Compared with conventional VC system in heat pump mode, rotary desiccant wheel cooling system not only can control the temperature but also can realize humidification. It also can be found that thermal energy is the main power to drive solid desiccant cooling system and the adopted refrigerant is natural working fluid. In other words, solid desiccant system is an energy-saving and environmentally friendly air conditioning method. Based on these reasons, numerous researches have been conducted in this field in terms of desiccant material, cycle mode and so on as concluded in previous works [1–4].

A brief review on previous work shows that available researches mainly focus on how to increase the energy utilization ratio or air quality of rotary desiccant wheel system, and electricity or gas burning is adopted to simulate the low grade heat source, mainly due to the merits of easy operation and maintenance. Solar energy with the advantages of cleanness and sustainability is widely acknowledged as a promising low grade thermal energy. Meanwhile, the obtained solar energy consists with required cooling load in cooing season, which means that when solar radiation is abundant, there is always a great need in cooling power. Also, solar technology has achieved remarkable progress with increasing attention on energy crisis in past decades. Based on these, solar powered solid desiccant air conditioning system especially solar powered solid desiccant cooling system gets more and more attention, and several actual systems have been built up. To the authors' knowledge, there is not yet a work that summarizes recent works done on solar powered rotary desiccant wheel air conditioning system. Hence, the objective of this article is to examine the progress in this area and to provide guidelines for designers. Emphasis should be placed on the fact that most of solid desiccant air conditioning system is developed to provide cooling power and then this paper focuses on summarize the development of solar powered rotary desiccant wheel cooling system. However, available results in heating season are also included although it is account for only a small part. The paper is categorized by whether auxiliary refrigeration system is installed. Within the first category it is ordered according to types of solar collector. For the second category, works are grouped by types of auxiliary refrigeration systems. For each system reviewed, attempt has been made to gather up the specifications of solar system, desiccant cooling system and overall performance of whole system.

2. Solar powered separate rotary desiccant wheel cooling system

2.1. Introduction of solar powered separate rotary desiccant wheel cooling system

2.1.1. Basic mode

Solar powered Desiccant wheel Evaporative Cooling System (SDECS) as shown in Fig. 1 is the widely adopted basic type of solar rotary desiccant wheel cooling system. This system is mainly consists of two subsystems: solar subsystem and desiccant cooling subsystem. In the solar subsystem, solar collector, auxiliary heater and water tank are the main components similar to conventional solar hot water system. Solar collector (1) is adopted to absorb solar radiation and heat up the water which is utilized in air heater (3) to heat up regeneration air. Water tank (2) acts like a heat storage unit which also helps to adjust the flux of water. The desiccant cooling subsystem operates on basic ventilation mode: process air from ambient condition is dehumidified and heated in desiccant wheel (4), then is cooled in sensible heat exchanger (5), heat exchanger wheel or plate type heat exchanger) and is further cooled in evaporative cooler (6), at last the air is supplied to conditioned space. Regeneration air from indoor condition flows through evaporative cooler (7), sensible heat exchanger (5), air heater (3) and desiccant wheel (4) in series. It can be seen that these two subsystems are connected by air heater (3), in which hot water from solar subsystem is utilized to heat up regeneration air in desiccant cooling subsystem.

Emphasis should be placed on the fact that auxiliary heat source (8) such as gas heater or electricity is adopted in some systems to ensure the continuous operation when solar energy is lack. Auxiliary heater can be installed in solar subsystem (mode 1) or installed directly in regeneration air side (mode 2).

2.1.2. Performance indicators

There exist several indices in different literatures to evaluate performance of solar solid desiccant cooling system. These indices are summarized and categorized in this part to make the following review more clear.

Nomenclature

A	Area of solar collector m^2
D	Diameter of desiccant wheel m
E	Electrical energy consumption W
d	Humidity ratio of the air *g water vapor/kg dry air*
Δd	Moisture removal in summer and moisture gained in summer (g/kg)
G	Radiation density of solar energy W/m^2
h	Enthalpy kJ / kg
m	Mass flow rate of air kg/s
PE	Primary energy W
Q	Thermal power$W$
RH	Relative humidity ratio %
r	Rotation speed r/h
T	Temperature °C
V	Volume of water tankm^3
θ	Inclination angle of solar collector °
η	Efficiency

Subscript

1,2,…,8	The corresponding states in Fig. 1
amb	Ambient condition
aux	Auxiliary thermal energy
ave	Average
dec	Solid desiccant cooling system
el	Based on electrical consumption
hs	Hybrid system
ic	Cooling power based on indoor air Eq. (2)
in	Inlet
ind	Indoor condition
out	Outlet
pa	Process air
pc	Cooling power from process air side
reg	Regeneration air
sol	Based on solar energy
sup	Supply air
th	Based on thermal consumption
tot	Based on total energy consumption
vc	Vapor compression subsystem

Abbreviation

AH	Auxiliary Heater
COP	Coefficient of Performance
DECS	Desiccant wheel Evaporative Cooling System
HPVT	Heat Pipe Vacuum Tube
SDECS	Solar powered Desiccant wheel Evaporative Cooling System
VCS	Vapor Compression System

2.1.2.1. Coefficient of performance COP. COP is a common and crucial performance index for an air conditioning system and following parameters are adopted to show the energy utilization ratio of solar rotary desiccant cooling system.

Thermal COP (COP_{th}) as shown in following equation is the widely adopted parameter to evaluate performance of solid desiccant cooling system. It is defined as the enthalpy change of process air divided by the thermal energy for regeneration:

$$COP_{th} = \frac{Q_{pc}}{Q_{reg,tot}} = \frac{m_{pa}(h_{pa,in} - h_{pa,out})}{Q_{reg,sol} + Q_{reg,aux}} = \frac{m_1(h_1 - h_4)}{m_7(h_8 - h_7)} \quad (1)$$

in which Q_{pc} means the handled cooling load from process air, $Q_{reg,tot}$ stands for the total regeneration heat required to drive system, and $Q_{reg,sol}$ and $Q_{reg,aux}$ are the thermal energy obtained in solar collector and auxiliary heater. Subscripts 1, 4, 7 and 8 are corresponding to the state in Fig. 1.

In Eq. (1) it can be seen that due to solid desiccant cooling system operate on fresh air mode, the system has to handle cooling load from fresh air as well as indoor air, and then enthalpy change of process air is adopted to calculate the cooling power. However, some researchers still adopt conventional method based on enthalpy change of indoor air to calculate COP as following:

$$COP^{*}_{th} = \frac{Q_{ic}}{Q_{reg}} = \frac{m_{pa}(h_{ind} - h_{pa,out})}{Q_{reg,sol} + Q_{reg,aux}} = \frac{m_1(h_5 - h_4)}{m_7(h_8 - h_7)} \quad (2)$$

in which enthalpy change between supply air and indoor air is calculated as cooling power.

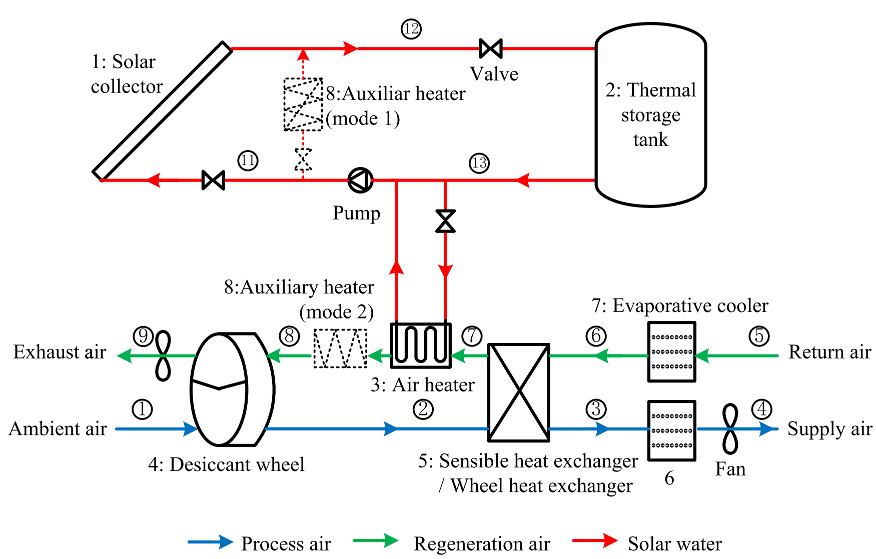

Fig. 1. Schematic figure of solar powered desiccant wheel evaporative cooling system (SDECS).

Electrical COP (COP_{el}) of the system can be calculated by:

$$COP_{el} = \frac{Q_{pc}}{E_{tot}} = \frac{m_{pa}(h_{pa,in} - h_{pa,out})}{E_{fan} + E_{pump} + E_{aux}} \tag{3}$$

$$COP^{*}_{el} = \frac{Q_c}{E_{tot}} = \frac{m_{pa}(h_{indoor} - h_{pa,out})}{E_{fan} + E_{pump} + E_{aux}} \tag{4}$$

in which E_{tot} is the total electrical consumption including fans E_{fan}, pumps E_{pump} and auxiliary consumption E_{aux} of the system.

If all energy consumption is considered to evaluate energy utilization ratio, following equations are considered:

$$COP_{tot} = \frac{Q_{pc}}{Q_{reg,tot} + E_{tot}} = \frac{m_{pa}(h_{pa,in} - h_{pa,out})}{Q_{reg,sol} + Q_{reg,aux} + E_{fan} + E_{pump} + E_{aux}} \tag{5}$$

$$COP^{*}_{tot} = \frac{Q_{ic}}{Q_{reg,tot} + E_{tot}} = \frac{m_{pa}(h_{indoor} - h_{pa,out})}{Q_{reg,sol} + Q_{reg,aux} + E_{fan} + E_{pump} + E_{aux}} \tag{6}$$

Also, some researches consider solar energy as a free thermal source and then following equation is adopted to describe the energy utilization ratio:

$$COP_{tot,aux} = \frac{Q_{pc}}{Q_{reg,aux} + E_{tot}} = \frac{m_{pa}(h_{pa,in} - h_{pa,out})}{Q_{reg,aux} + E_{fan} + E_{pump} + E_{aux}} \tag{7}$$

Solar thermal COP ($COP_{th,sol}$) is calculate by:

$$COP_{th,sol} = \frac{Q_{pc}}{Q_{sol}} = \frac{m_{pa}(h_{pa,in} - h_{pa,out})}{G \cdot A} \tag{8}$$

2.1.2.2. Solar fraction SF. As a solar powered system, solar fraction *SF* is an important parameter to estimate the contribution of solar radiation. It is defined as the ratio of energy provided by solar collectors for regeneration to the total energy required for regeneration including the auxiliary heater:

$$SF = \frac{Q_{reg,solar}}{Q_{reg,tot}} = \frac{Q_{reg,solar}}{Q_{reg,solar} + Q_{reg,auxiliary}} \tag{9}$$

2.2. Research progress on solar water collector powered system

2.2.1. Flat plate solar collector powered system

Flat plate solar collector is the most common solar collector for use in solar water heating system. It mainly consists of an insulated metal box with transparent cover and dark-colored plate absorber. Solar radiation is absorbed by the plate absorber and transferred to water. The provided temperature of flat plate solar collector is about 30–80 °C. Also, the manufacture of flat plate solar collector is relatively mature and cost is relatively low. Therefore, lots of researchers adopt flat plat solar collector to drive the operation of solid desiccant cooling system.

Some researchers integrate flat plate solar collector with conventional DECS: Preisler et al. [5] investigated annual performance of an actual SDECS by experiment. The experimental demonstration was built in an office building in Vienna, Austria. Actual monitoring data of the system was compared with simulated data of a conventional compression chiller by TRNSYS 17. Results showed that average $COP*_{el}$ of SDECS in winter could reach 7.0, and in 2010 the SDECS achieved 60.5% primary energy savings compared to the reference system. The highest energy saving was obtained in winter for heating and humidity recovery purposes of fresh air, moderate energy saving was obtained in summer for cooling and humidity control, and there was no obvious energy saving in transition time. Also, performance of a solar assisted heating and desiccant cooling system was investigated in Baghada Iraq by Khalid et al. [6]. In winter, heat collected from solar collector was supplied to conditioned room for heating purpose, and a rock bed storage unit and auxiliary heat source were adopted. In summer, a ventilation mode was utilized to provide cooling power. A model was developed to study both heating and cooling performance of the system and to analyze effects of main operation parameters on system performance. It was found that regeneration temperature of 62 °C could be reached by solar collector alone, auxiliary heat source was required to achieve higher regeneration temperature. Also, solar desiccant cooling system can provide satisfied supply air to conditioned space under local weather condition, and performance of desiccant cooling system relied mainly on effectiveness of sensible heat exchanger and evaporative cooler, while effect of dehumidifier was relatively small.

Besides, several modified systems are investigated to obtain improved performance. Guidara et al. [7] developed pre-cooling and final-cooling modes to satisfy the required cooling capacity. Schematic figure of the proposed system is shown in Fig. 2: two indirect evaporative coolers are installed before ambient air entering desiccant wheel and before process air entering conditioned space. Performance of the system was simulated in three representative cities with different climatic conditions in Tunisia. Meanwhile, three different operation functions including conventional DECS mode, with pre-cooling mode and with pre-cooling, final-cooling mode, were compared and analyzed. Simulation results showed that basic DECS mode was feasible under relatively cold and humid condition in Bizerte. However, for dry condition in Remada and moderate condition in Djerba, systems with pre-cooling mode and with pre-cooling, final-cooling mode had to be applied to cover the corresponding demands. Also, it is found that the conditioned space with respect to each mode of functioning has comfortable environment for occupants.

Enteria et al. [8–11] proposed combined solar thermal and electric desiccant cooling system as shown in Figs. 3 and 4. In the system, solar powered desiccant cooling system operated in daytime to produce required cooling power, an electric heater was connected with flat plate solar collector in parallel as heat source in nighttime operation for thermal energy storage, and an air compressor was adopted to remove water from the tank in case of freezing. Also, compared with conventional SDECS (Fig. 1), a small heat exchanger was adopted in this system to recovery cooling capacity from return air. An experimental system was constructed and tested during nighttime and daytime within typical days [9–10]. Measured results showed that the system could provide satisfied cooling capacity to conditioned room, and almost 3/4 of thermal energy was from solar collector. The detailed data is summarized in Table 1. Also, Enteria et al. [8] extended this system to different climatic conditions in East-Asia and evaluated the potential performance with different desiccant material including silica gel and Titanium Dioxide. Complete system model was established in TRNSYS and validated by experimental results [12]. With use of the model, simulation work was conducted in six representative cities from temperature, sub-tropical and tropical climates. Performance of solar subsystem, desiccant subsystem, building subsystem and total system were examined. Results showed that system with TiO_2 wheel could produce lower supply air humidity ratio as well as temperature compared with the system using SiO_2, and specification of the system varied depending on the climatic conditions: bigger collector surface, larger thermal storage tank, higher air flow rate and more electrical consumption were required in tropic climate. Also, COP_{th} of the system was between 1.5 and 3. Further, the researchers investigated performance of this system based on energy and exergy analysis methods to improve system operation in summer days [10]. Analyzed results demonstrated that the main contributors of energy losses and exergy destructions were the solar collector, water pipe, electric heater and storage tank, and then improvements on these equipment were crucial for increasing system performance.

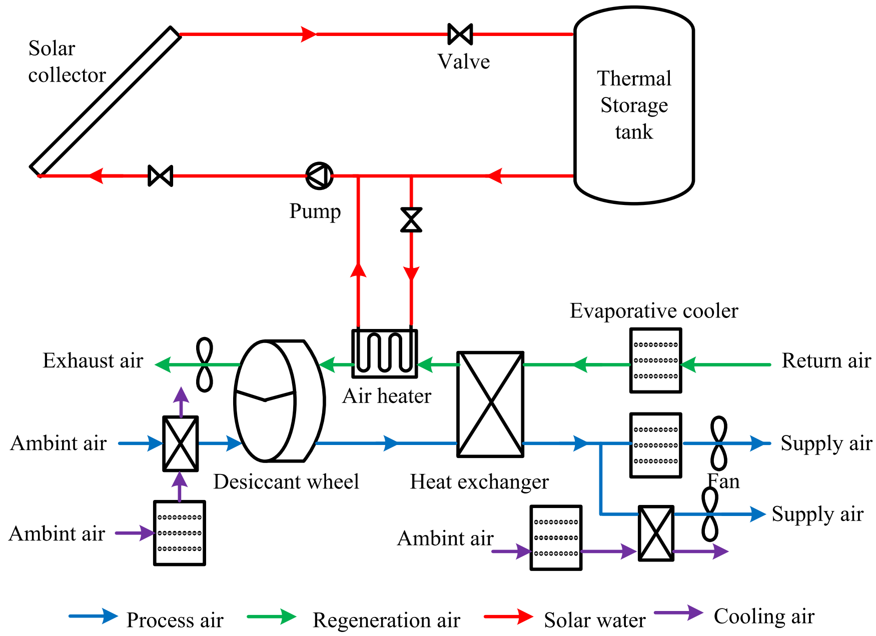

Fig. 2. Schematic figure of system with pre-cooling & final-cooling [7].

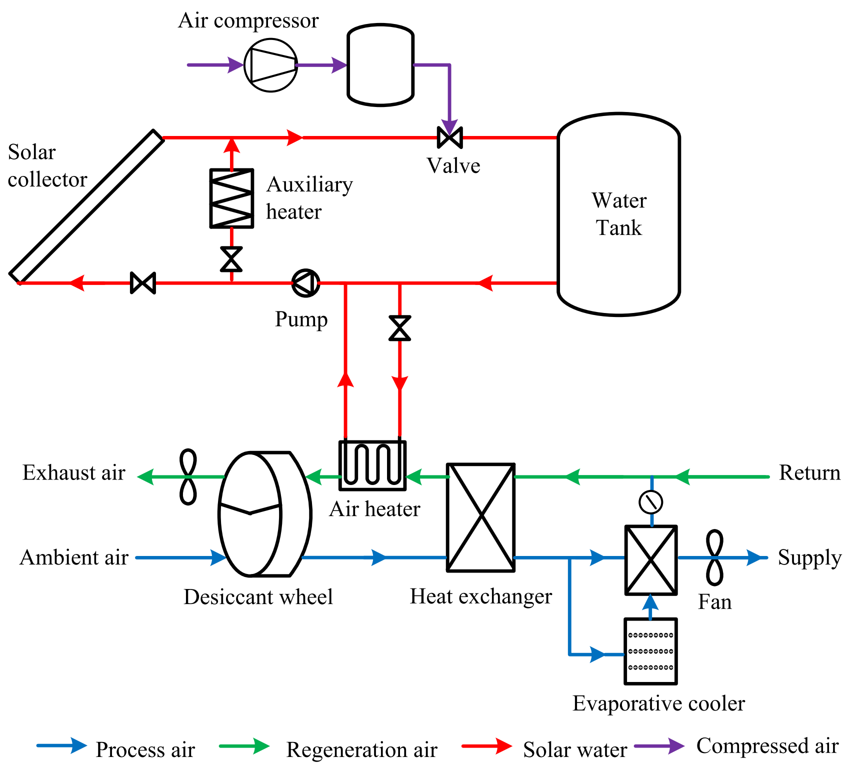

Fig. 3. Schematic figure of modified SDECS [9].

White et al. [13] proposed a plate type water collector driven SDECS with indirect evaporative cooler and direct evaporative cooler installing in series and without backup heat source as shown in Fig. 5. A simulation model was developed in TRNSYS to study performance of the system in three cities in Australia: the warm temperate climates of Melbourne, Sydney and the tropical climate of Darwin. It was found that this type of two-stage evaporative cooling process could enhance the sensible cooling capacity. Especially at low primary air humidity, temperature of supply air could be significantly reduced. Also, effects of air flow rate and area of solar collector were discussed. Results showed that increasing collector area and air flow rate reduced the frequency of high temperature events in the occupied space. In the warm temperate climate (Melbourne and Sydney), high ventilation rates enabled comfort conditions to be maintained at or near acceptable levels in the occupied space, without the use of a backup thermal source. In the extreme weather events, evaporative cooling appeared to be the dominant mechanism for cooling the occupied space.

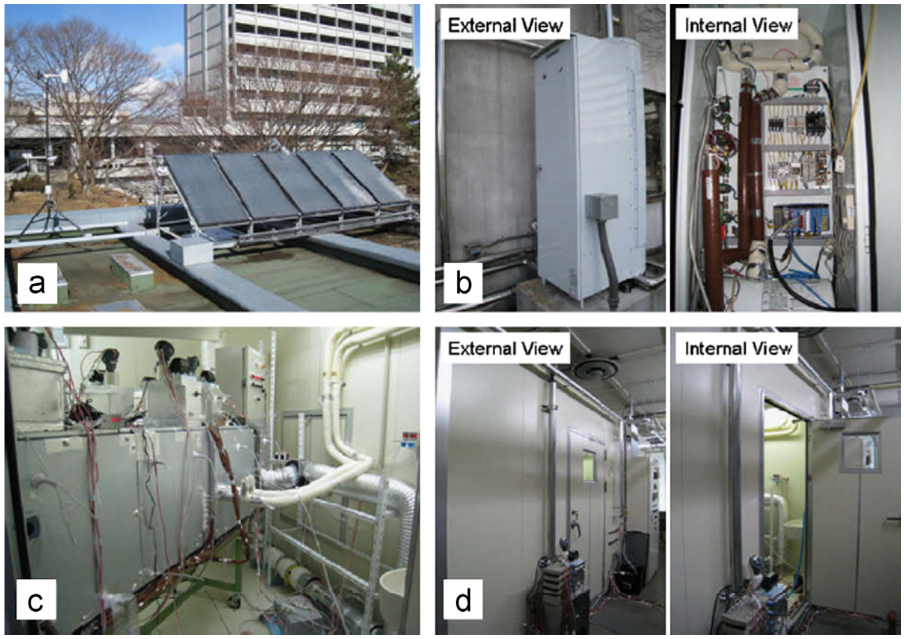

Fig. 4. Total system actual view: (a) solar collector; (b) thermal storage and auxiliary heater; (c) desiccant cooling; (d) controlled chambers [9].

Table 1
Summary of performance of separate solar rotary desiccant wheel cooling system.

Ref.	Solar subsystem	Desiccant cooling subsystem	Overall system performance	
[5]	Type: flat plate water collector Area:285 m^2 Volume of water tank:15 m^3 Auxiliary heater: NO	Type: Desiccant wheel Evaporative Cooling System (DECS) Desiccant material: lithium chloride	Vienna, Austria (experiment)	Summer: $\Delta d = 0–4.4\ g/kg$ Winter: $\Delta d = 0–6.6\ g/kg$ Annual average $COP^{*}_{el} = 7$
[6]	Type: flat plate water collector Area: 5.4 m^2 Auxiliary heater: mode 2	Type: DECS Desiccant material: silica gel	Baghada, Iraq (simulation)	$T_{amb} \approx 40.6\ ^{\circ}C$ $d_{amb} \approx 10.4–12\ g/kg$ $T_{reg} \approx 45–90\ ^{\circ}C$ $T_{sup} \approx 19–22\ ^{\circ}C$ $d_{sup} \approx 4–10\ g/kg$ $COP_{tot,aux} = 1.5–5.5$
[7]	Type: flat plate water collector Auxiliary heater: NO	Type: DECS Desiccant material: silica gel	Bizerte, Tunisia (simulation)	$T_{amb} \approx 24\ ^{\circ}C$ $d_{amb} \approx 10\ g/kg$ $T_{reg} = 70\ ^{\circ}C$ $T_{sup} = 20.3\ ^{\circ}C$ $d_{sup} = 7.4\ g/kg$
			Remada, Tunisia (simulation)	$T_{amb} \approx 48\ ^{\circ}C$ $d_{amb} \approx 10\ g/kg$ $T_{reg} = 70\ ^{\circ}C$ $T_{sup} = 24.7\ ^{\circ}C$ $d_{sup} = 9.4\ g/kg$
			Djerba, Tunisia (simulation)	$T_{amb} \approx 38\ ^{\circ}C$ $d_{amb} \approx 14\ g/kg$ $T_{reg} = 70\ ^{\circ}C$ $T_{sup} = 22\ ^{\circ}C$ $d_{sup} = 7.3\ g/kg$
[8]	Type: Flat plate & water Outlet water temperature: 90 °C Efficiency: $\eta = 0.5–0.7$	Type: DECS Desiccant material: titanium dioxide or silica gel	Beijing, China (simulation)	Required inclination angle:39° Required area of solar collector:12 m^2 Volume of tank: 0.644 m^3 $T_{amb} \approx 31\ ^{\circ}C$ $d_{amb} \approx 17\ g/kg$ Performance of SiO_2 wheel: $T_{sup} = 23\ ^{\circ}C$ $d_{sup} = 7.6\ g/kg$ $COP_{th} = 1.3$ $COP_{el} = 1.5$ Performance of TiO_2 wheel: $T_{sup} = 22\ ^{\circ}C$ $d_{sup} = 7.4\ g/kg$ $COP_{th} = 1.5$ $COP_{el} = 1.7$ Required area of solar collector:10 m^2

Table 1 (*continued*)

Ref.	Solar subsystem	Desiccant cooling subsystem	Overall system performance	
				Volume of tank: 0.644 m^3 $T_{amb} \approx 30$ °C $d_{amb} \approx 17$ g/kg Performance of SiO_2 wheel: $T_{sup}=23$ °C $d_{sup}=7.7$ g/kg $COP_{th}=1.5$ $COP_{el}=2.7$ Performance of TiO_2 wheel: $T_{sup}=22.5$ °C $d_{sup}=7.5$ g/kg $COP_{th}=1.7$ $COP_{el}=3.0$
			Tokyo, Japan (simulation)	Required inclination angle: 35°
			Taipei (simulation)	Required inclination angle: 25° Required area of solar collector:14 m^2 Volume of tank: 0.966 m^3 $T_{amb} \approx 32.5$ °C $d_{amb} \approx 19.5$ g/kg Performance of SiO_2 wheel: $T_{sup}=24$ °C $d_{sup}=7.7$ g/kg $COP_{th}=2.1$ $COP_{el}=2.8$ Performance of TiO_2 wheel: $T_{sup}=23$ °C $d_{sup}=7.5$ g/kg $COP_{th}=2.3$ $COP_{el}=3.0$
			Hong Kong, China (simulation)	Required inclination angle:22° Required area of solar collector:12 m^2 Volume of tank: 0.966 m^3 $T_{amb} \approx 32$ °C $d_{amb} \approx 19$ g/kg Performance of SiO_2 wheel: $T_{sup}=24$ °C $d_{sup}=7.8$ g/kg $COP_{th}=2.1$ $COP_{el}=3.0$ Performance of TiO_2 wheel: $T_{sup}=23$ °C $d_{sup}=7.3$ g/kg $COP_{th}=2.3$ $COP_{el}=3.3$
			Manila, Philippines (simulation)	Required inclination angle:14° Required area of solar collector:14 m^2 Volume of tank: 1.288 m^3 $T_{amb} \approx 34$ °C $d_{amb} \approx 18.5$ g/kg Performance of SiO_2 wheel: $T_{sup}=24$ °C $d_{sup}=10$ g/kg $COP_{th}=1.9$ $COP_{el}=2.5$ Performance of TiO_2 wheel: $T_{sup}=23$ °C $d_{sup}=7.6$ g/kg $COP_{th}=2.1$ $COP_{el}=2.8$
			Singapore (simulation)	Required inclination angle:1° Required area of solar collector:14 m^2 Volume of tank: 1.288 m^3 $T_{amb} \approx 31$ °C $d_{amb} \approx 20$ g/kg Performance of SiO_2 wheel: $T_{sup}=24$ °C $d_{sup}=10$ g/kg $COP_{th}=2.5$ $COP_{el}=2.6$ Performance of TiO_2 wheel: $T_{sup}=23$ °C $d_{sup}=7.8$ g/kg

Table 1 (*continued*)

Ref.	Solar subsystem	Desiccant cooling subsystem	Overall system performance	
				$COP_{th}=2.9$ $COP_{el}=3.0$
[9] [11]	Type: flat plate water collector Area: 10 m^2 Volume of water tank:0.332 m^3 Average efficiency: 0.53 Auxiliary heater: Mode 1	Type: DECS Desiccant material: silica gel Diameter of desiccant wheel: 400 *mm* Width of desiccant wheel:200 *mm* Rotation speed:20 *r/h*	Sendai, Japan (experiment)	**Condition 1** [9]**:** $T_{amb} \approx 31\ ^{\circ}C$ $d_{amb} \approx 16.5\ g/kg$ $T_{sup} \approx 26\ ^{\circ}C$ $d_{sup} \approx 11\ g/kg$ $COP_{tot}=0.25$ **Condition 2** [11]**:** $T_{amb} \approx 30\ ^{\circ}C$ $RH_{amb} \approx 60\%$ $T_{reg} \approx 60/65/70/75\ ^{\circ}C$ $T_{sup} \approx 26.1/26.4/26.7/27.0\ ^{\circ}C$ $d_{sup} \approx 14.3\ g/kg$ $COP_{tot}=0.44/0.43/0.40/0.35$
[13]	Type: flat plate water collector Area: 100 m^2 Volume of water tank:30 m^3 Auxiliary heater: NO	Type: Hybrid direct evaporative cooling and indirect evaporative cooling system	Melbourne, Austria (simulation) Conditioned space:3000 m^2	6.18 air-changes/h $T_{amb} \approx 24–35\ ^{\circ}C$ $d_{amb} \approx 5–18\ g/kg$ $T_{ind}=22–30\ ^{\circ}C$ $d_{ind}=10–18 g/kg$ $COP^{*}_{th}=0.15–0.5$
[14]	Type: heat pipe vacuum tube water collector Area: 205–300 m^2 Outlet water temperature: 60–85 °C Efficiency: 0.5–0.7 Auxiliary heater: Mode 2	Type: DECS Desiccant material: silica gel	La Rochelle, France (simulation)	$A=300\ m^2$ representative $\eta=0.63$ seasonal $\eta=0.54$ representative $SF=0.93$ seasonal $SF=0.96$
			Bolzano, Italy (simulation)	$A=245\ m^2$ representative $\eta=0.5$ seasonal $\eta=0.51$ representative $SF=0.87$ seasonal SF=0.97
			Berlin, Germany (simulation)	$A=205\ m^2$ representative $\eta=0.56$ seasonal $\eta=0.51$ representative $SF=0.97$ seasonal $SF=0.9$
[17]	Type: heat pipe vacuum tube water collector Area: 40 m^2 Volume of water tank:2.5 m^3 Outlet water temperature: 60–85 °C Efficiency: 0.6–0.8 Auxiliary heater: NO	Type: DECS Desiccant material: silica gel Diameter of desiccant wheel:1220 *mm* Width of desiccant wheel:200 *mm* Rotation speed: 8 *r/h*	La Rochelle, France (experiment)	$T_{amb}=23–30\ ^{\circ}C$ $d_{amb}=12–14\ g/kg$ $T_{ind} < 26.5\ ^{\circ}C$ $d_{ind}=12–14\ g/kg$ $T_{sup} < 20\ ^{\circ}C$ $T_{reg} \approx 57\ ^{\circ}C$ (almost stable) $COP^{*}_{th} \approx 0.4$ $COP^{*}_{el} \approx 4.3$
[20]	Type: Vacuum tube water collector Area: 550 m^2 Average efficiency: 0.75–0.85 Auxiliary heater: Mode 1	Type: Two-stage DECS Desiccant material: composite silica gel and lithium chloride Diameter of desiccant wheel: 2800*mm* Width of desiccant wheel: 100 *mm* Rotation speed: 3–10 *r/h*	Shanghai, China (simulation)	$T_{reg}=70–90\ ^{\circ}C$ $T_{sup}=20.4–26.2\ ^{\circ}C$ $d_{sup}=14.1–14.7\ g/kg$ $COP_{th}=1.28$
			Berlin, Germany (simulation)	$T_{reg}=50–70\ ^{\circ}C$ $T_{sup}=16.7–22.0\ ^{\circ}C$ $d_{sup}=10.7–11.3\ g/kg$ $COP_{th}=0.9$
[21]	Type: flat plate air collector Area: 100 m^2 Outlet water temperature: 44 °C Auxiliary heater: Mode 2	Type: DECS Desiccant material: silica gel	Hong Kong, China (simulation)	annual $COP_{th}=1.38$ annual $SF=17\%$ under a typical day: $T_{reg}=55\ ^{\circ}C$ $T_{sup}=22\ ^{\circ}C$ $d_{sup}=8–12\ g/kg$
[23]	Type: porous type solar air heater Area:1.2 m^2 Volume of water tank:0.332 m^3 Average efficiency: 0.2–0.7 Auxiliary heater: NO	Type: DECS Desiccant material: calcium chloride Diameter of desiccant wheel: 400 *mm* Width of desiccant wheel:600 *mm* Rotation speed:120 *r/h*	Egypt (experiment)	$T_{amb} \approx 28–38\ ^{\circ}C$ $T_{reg} \approx 30–60\ ^{\circ}C$ $\Delta d \approx 2–7\ g/kg$ $COP_{th,sol} \approx 0.65–0.9$
[24]	Type: Evacuated tube air collector Area:120 m^2 Average efficiency: 0.3–0.6 Auxiliary heater: Mode 2	Type: Two-stage DECS Desiccant material: composite silica gel and lithium chloride	Dezhou, China (experiment)	In cooling mode: $T_{amb}=26.7–32.0\ ^{\circ}C$ $d_{amb}=18\ g/kg$ $T_{reg}=93.9\ ^{\circ}C$ $T_{sup} \approx 18–20\ ^{\circ}C$ $d_{sup} \approx 6–10\ g/kg$ $COP_{th}=0.8–1.2$ In heating mode:

Table 1 (*continued*)

Ref.	Solar subsystem	Desiccant cooling subsystem	Overall system performance	
				$T_{amb} \approx$ 10–15 °C d_{amb} = 18 g/kg T_{reg} = 45 °C $T_{sup} \approx$ 21–23 °C Δd: 4g/kg
[25]	Type: evacuated tube air collector Area:92.4 m^2 Auxiliary heater: NO	Type: Two-stage DECS Desiccant material: composite silica gel and lithium chloride	Dezhou, China (simulation) Room area:169m^2	In cooling mode: T_{sup} = 20.4 °C T_{ind} = 22.4 °C COP_{th} = 0.34 SF = 0.75 In heating mode: SF = 0.61
[26]	Auxiliary heater: NO	Type: Two-stage DECS Desiccant material: silica gel Diameter of desiccant wheel:300 *mm*	(simulation)	T_{amb} = 35 °C d_{amb} = 14.5 g/kg T_{sup} = 16.5 °C d_{sup} = 9.8 g/kg COP_{th} = 1.25
[27]	Type: PVT air collector Area:105 m^2 Volume of tank:0.65 m^3 Efficiency: 0.39 Area of PV shed:300 m^2 Area of PV facade:225 m^2 Auxiliary heater: NO	Type: DECS Desiccant material: silica gel Diameter of desiccant wheel:2100 *mm* Width of desiccant wheel:360 *mm* Rotation speed: 20 *r/h*	Mataro, Spain (simulation) Conditioned space:3200m^2	$T_{amb} \approx$ 25–38 °C $d_{amb} \approx$ 10–15 g/kg $T_{reg} \approx$ 70 °C $T_{sup} \approx$ 15–21 °C $d_{sup} \approx$ 7–10 g/kg COP_{th} = 0.518 (monthly average)

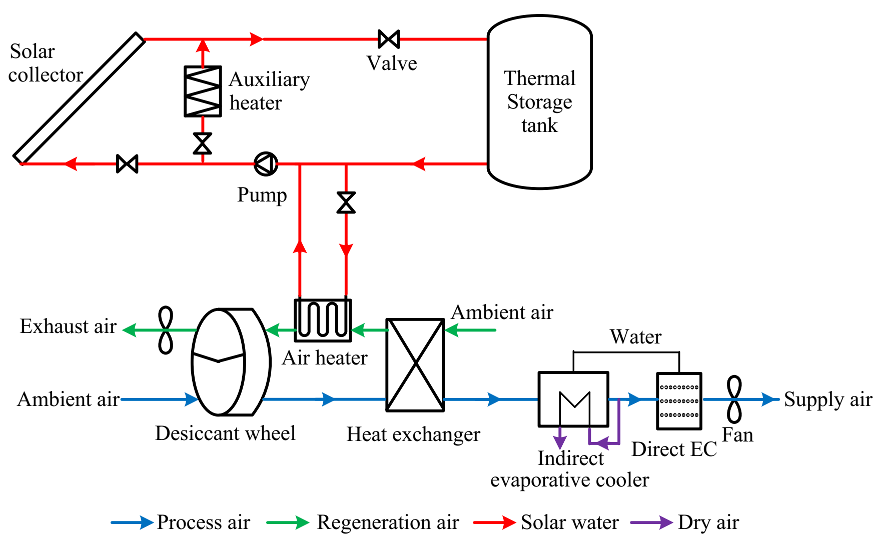

Fig. 5. Schematic figure of SDECS with indirect & direct evaporative cooling [13].

2.2.2. *Vacuum tube solar collector powered system*

Bourdoukan et al.[14] proposed that low efficiency of flat-plate collectors resulting in low potential of solar use in solid desiccant cooling, and then heat pipe vacuum tube (HPVT) collectors was adopted in the study to drive conventional DECS. Mathematical models of HPVT collectors and water tank were established and validated in the study, and then these models were combined with existed desiccant wheel models [15–16] to develop integrated SDECS mathematical model. Based on this system model, performance of HPVT driven DECS was simulated to provide cooling capacity to a building with area of 1350 m^2 under three locations including La Rochelle, Bolzano and Berlin to study the potential of such applications. It was assumed that: (1) when ambient temperature exceeded 26 °C or ambient humidity ratio exceeded 10.8 g/kg, HPVT driven DECS operated to handle both sensible and latent heat, otherwise, only an indirect evaporative cooling was utilized to realize air conditioning; (2) an energy backup was installed to ensure enough cooling power was delivered. Simulation results over a summer season demonstrated that the system could maintain the building temperature and humidity at a comfort level (indoor temperature is lower than 26.5 °C and indoor humidity ratio is less than 11.8 g/kg) for different locations from relatively dry to hot and moderately humid. Meanwhile, daily efficiency of HPVT varied from 50% to 64% and the daily solar fraction varied from 87% to 97%, and the corresponding seasonal overall efficiency and solar fraction were higher than 51% and 90%, respectively. Detailed simulation results with respect to different locations are listed in Table 1 for reference. Based on this research, Bourdoukan et al.[17] further developed an experimental setup of HPVT powered DECS. Actual operation data not only validated the

feasibility of such system but also demonstrated that HPVT collector could obtain high temperature level and stable duration of regeneration temperature compared with flat plat type. Under experimental condition with a moderately humid day (T_{amb}=23–30 °C, d_{amb}=12–14 °C), indoor environment could maintain at comfort condition of 26.5 °C and 12–14 g/kg, COP_{th}* of the systems was 0.4, while the performance indicator defined on electrical energy consumption basis $COP*_{el}$ was evaluated at 4.3 over the day. Besides, effects of outside and regeneration conditions were analyzed, and outside humidity ratio was found to be the most sensitive parameter.

Ge et al. [18–19] pointed out that the released adsorption heat in dynamic dehumidification process was the main reason causing decreased performance of rotary desiccant wheel cooling system. And then inter-cooling two-stage rotary desiccant wheel cooling system (TSDCS) was developed to obtain improved performance and it was found that TSDCS had the merit of low regeneration temperature as well as high thermal COP. Further study on solar powered TSDCS as shown in Fig. 6 was conducted in Ref. [20]. In the research, performance of a solar driven TSDCS and a VCS were simulated to provide cooling for one floor in a commercial office building in two cities with different climates: Berlin and Shanghai. Both thermodynamic and economic performance of the two systems were evaluated and compared. Results show that the desiccant cooling system was able to meet the cooling demand and provided comfortable supply air in both regions. The required regeneration temperatures were 55 °C in Berlin and 85 °C in Shanghai. As compared to the vapor compression system, the desiccant cooling system had better supply air quality and consumed less electricity. The results of the economic analysis demonstrate that the dynamic investment payback periods were 4.7 years in Berlin and 7.2 years in Shanghai.

2.3. Research progress on solar air collector powered system

2.3.1. Solar air collector powered system

Previously mentioned systems use solar water collector to heat up regeneration air. Solar water collector has the merits of high heat flux, but a water-air heat exchanger is required in the system to realize the heat transfer between hot water and regeneration air. When solar air collector is utilized, there is no need to install a heat exchanger component, the volume and construction of solar solid desiccant cooling system is much more compact and simple.

Fong et al. [21] conducted simulation optimization of SDECS under subtropical climate in Hong Kong. A simulation model of SDECS was established using TRNSYS 16.01, in which performance of silica gel desiccant wheel was predicted by fitted efficiency relationship. Solar air collector instead of conventional solar water collector was adopted as regeneration heat source in the system, and robust evolutionary algorithm was developed to achieve maximal annual average of solar fraction *SF*. Simulation results showed that monthly average *SF* was in the range from 8% to33%, and the yearly average was 17%. The monthly average COP_{th} was from 1.08 to 1.60, with the mean of 1.38. The overall performance of SDECS showed that it was a technically feasible option in Hong Kong for air-conditioning purpose.

Hatami et al. [22] adopted solar air collector to power a DECS, investigation work was carried out to obtain the optimized surface area of solar air collector based on a mathematical model in TRNSYS. Results showed that under the simulation condition (T_{amb}=30 °C, d_{amb}=25 g/kg, T_{reg}=90 °C), necessary area of the solar collector surface could be decreased from 33.1 m^2 to 15.1 m^2 by using all of parameters of desiccant wheel in optimum quantities. Necessary area of solar collector surface decreased with the increasing of outdoor air dry bulb and wet bulb temperature.

Kabeel et al. [23] adopted porous type solar air heater to drive solid desiccant cooling system. Schematic figure of solar collector is shown in Fig. 7, it can be seen that ambient air is pumped into the channels within solar collector and heated by solar radiation directly. Experimental setup was built to investigate adsorption as well as regeneration performance of the system with respect to different ambient air conditions and radiation intensity. Results showed that the system was highly effective in regeneration process, and empirical equations to calculate performance of desiccant wheel under different operation conditions were obtained. Detailed system performance is summarized in Table 1.

There also some researches focusing on solar air collector powered TSDCS. Li et al. [24,25] combined solar vacuum tube air collector with the two-stage rotary desiccant wheel cooling/heating system to provide cooling/heating power for a conditions pace in Dezhou China. Firstly, performance of the system was tested and then a simulation model was established in Matlab Simulink to obtain optimized design of solar air collector. Both experimental and simulation results showed the system could provide satisfied supply air especially in hot and humid climate conditions, and solar heating with desiccant humidification can improve the indoor comfort significantly in winter. Also, there was optimal design of solar collector to obtain higher cooling/heating power and *SF*. Detailed data are summarized in Table 1.

Based on the research of two-stage system, Ali et al.[26] further developed one-rotor six-section solar powered desiccant cooling system, in which one cross section of desiccant wheel was divided into six parts, two pre-cooling parts were added to cool desiccant wheel after regeneration process as shown in Fig. 8, and then dehumidification capacity of the system was improved. Simulation model was established to investigate effects of main operation parameters on system performance. It was found that payback time of this system was 4.89 years compared with conventional VC system.

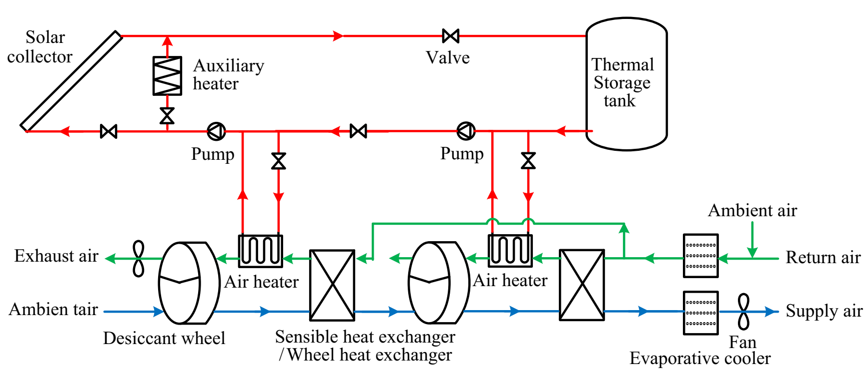

Fig. 6. Schematic figure of two-stage rotary desiccant wheel cooling system [20].

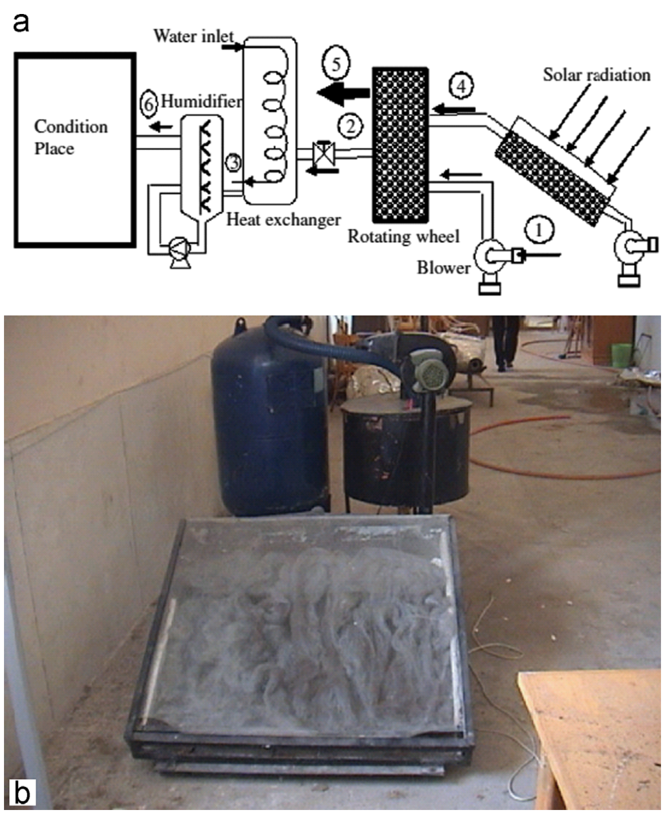

Fig. 7. Schematic figure of system investigated in Ref. [23].

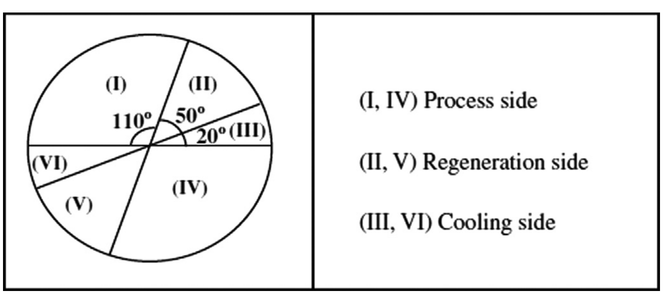

Fig. 8. Cross section of one rotor six section desiccant wheel [26].

2.3.2. Solar air collector and PV powered system

Photovoltaic (PV) is an important application of solar energy, in most of cases, there is a group of air circulating behind the PV panel to decrease the temperature of PV panel and thus improves the electrical efficiency, and if the heated up air is utilized as thermal source, this component is named as PVT. PVT can be combined with SDECS to produce cooling/heating power.

In a library in Mataro, PVT and solar air collector heating system were combined together to regenerate a DECS [27]. The hybrid solar system included 525 m^2 PV panel (PV façade and PV shed) and 105 m^2 solar air collectors, the collector and PVT were connected in series to provide regeneration heat for DECS as shown in Fig. 9. Different system operation modes were realized by adjusting the volume flow rate of process air and regeneration air, and operation modes were determined based on temperatures of ambient and indoor air conditions. A system model was established and validated by actual operation data on a typical day, and then the model was adopted to analyze performance of the system in summer. It was found that cooling power of 43580 kWh was obtained which could achieve *SF* of 0.75 at least and an average COP_{th} of 0.518 was achieved.

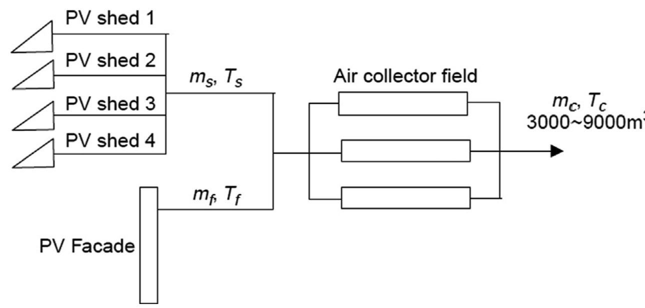

Fig. 9. PVT solar air system adopted in Ref. [27].

3. Solar powered hybrid rotary desiccant wheel cooling system

Rotary desiccant wheel system has good capacity of handling latent load, and conventional VCS can effectively remove sensible load compared with evaporative cooling process. Therefore, there exist some investigations on hybrid solid desiccant cooling system. In this part, a brief review on solar powered hybrid rotary desiccant wheel cooling systems is conducted.

3.1. Introduction of hybrid SDECS and VCS

3.1.1. Basic mode

VCS is the most mature and common refrigeration technology, and then most of the researchers combine SDECS with conventional VCS. Schematic figure of hybrid SDEC&VCS is shown in Fig. 10: for process air, ambient air first is pumped through desiccant wheel, in which water vapor is removed, a sensible heat exchanger is installed in the following to recover the released adsorption heat and heat up regeneration air preliminarily, and then a group of air coil powered by conventional VC system is adopted to cool process air to satisfied supply state; for regeneration air, preliminarily heated process air is further heated up in the heater driven by solar collecting system and then is introduced into desiccant wheel to realize regeneration. It can be seen that the hybrid system effectively combines the advantages of SDECS and VCS, which are utilized to remove latent and sensible load respectively. Also, it should be noted that due to there exist released adsorption heat in desiccant wheel and then SDECS is always installed before VCS in the hybrid system. Meanwhile, VCS can operate at higher evaporation temperature due to latent load has been removed in SDECS, which results in higher COP. In other words, hybrid SDEC&VCS can also realize energy saving by separate sensible and latent load handling method.

3.1.2. Performance indicators

Performance parameters introduced in Part 2.1.2 still can be adopted to describe hybrid system, and different subscripts "*dec*" "*vc*" and "*hs*" stand for solar desiccant cooling system, vapor compression system and the whole hybrid system respectively. For example, $COP_{tot,dec}$ means the total COP of desiccant cooling system, which can be calculated by Eq. (5), and $COP_{tot,hs}$ is the total COP of whole hybrid system which is defined as:

$$COP_{tot,hs} = \frac{Q_{pc,hy}}{Q_{reg,tot} + E_{tot,dec} + E_{tot,vc}} = \frac{m_{pa}(h_{pa,in} - h_{\sup})}{Q_{reg,sol} + Q_{reg,aux} + E_{fan} + E_{pump} + E_{compressor} + E_{aux}} \quad (10)$$

There are two kinds of energy sources including electricity and thermal energy in the hybrid system, and then primary energy

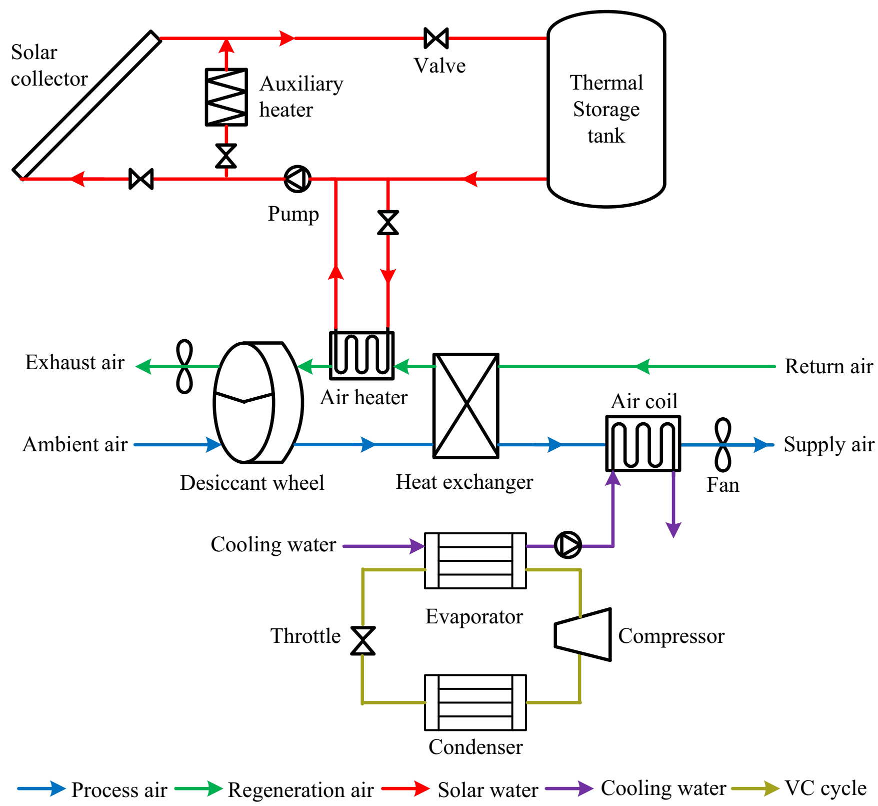

Fig. 10. Schematic figure of basic hybrid SDECS and VCS.

consumption (*PE*) is a better performance indicator:

$$PE = \frac{Q_{reg,aux}}{\eta_{th}} + \frac{E_{tot}}{\eta_e} \tag{11}$$

and COP based on primary energy is calculated by:

$$COP_{tot,pe,hs} = \frac{Q_{pc,hy}}{PE} = \frac{m_{pa}(h_{pa,in} - h_{\sup})}{\frac{Q_{reg,aux}}{\eta_{th}} + \frac{E_{fan} + E_{pump} + E_{compressor} + E_{aux}}{\eta_e}} \tag{12}$$

in which η_{th} and η_{te} mean the energy transfer efficiency to produce auxiliary thermal energy and electricity.

When total energy consumption is considered, the solar fraction is:

$$SF_{tot} = \frac{Q_{reg,solar}}{Q_{reg,tot} + E_{tot}} = \frac{Q_{reg,solar}}{Q_{reg,solar} + Q_{reg,auxiliary} + E_{fan} + E_{pump} + E_{aux}} \tag{13}$$

Hybrid system is proposed to decrease the electrical consumption of conventional VCS, and then electricity saving ration E_{save} and primary energy saving ratio PE_{save} compared with conventional VCS with the same cooling power are utilized in some research:

$$E_{save} = \frac{E_{tot,vc} - E_{tot,hs}}{E_{tot,vc}} \tag{14}$$

$$PE_{save} = \frac{PE_{tot,vc} - PE_{tot,hs}}{PE_{tot,vc}} \tag{15}$$

3.2. Research progress on hybrid SDECS and VCS (SDEC&VCS)

Researchers from UK established a mathematical model to predict the performance of hybrid SDEC&VCS [28]. Then, feasible study in Europe was conducted with use of real summer time meteorological data [29] [30]. Several representative cities in Europe from north to south were selected as the sample locations, in which hot days occurred in July 1996 were considered. It was assumed that supply air was maintained at 18 °C in the simulation process. Simulation results outlined that solar powered single-stage rotary desiccant wheel cooling system was feasible in most of central Europe, Atlantic and inland regions of south Europe. Latent load rather than available solar energy was the prime constraint on the utilization of desiccant cooling. Performance of the system was evaluated by energy saving ratio compared with conventional gas powered desiccant cooling system. It was found that except for Oslo, gas energy savings of 25.1–46.5% was obtained. The gas energy saving of 93% achieved in Oslo, because the latent load in Oslo was much lower than those in other locations.

Finocchiaro et al. [31] pointed out that due to the cooling capacity of return air was limited in DECS, relatively high outlet temperature which was rarely lower than 26 °C was obtained. In order to overcome this problem, a packed wet heat exchanger was proposed to replace sensible heat exchanger to realize much more sensible load removal. Detailed configuration and pictures of the wet heat exchanger is shown in Fig. 11. Then, an experimental setup of hybrid SDEC&VCS was built to investigate the detailed performance. Experimental results show that due to the optimization of the indirect evaporative cooling process, a supply temperature in the range of 21–22 °C can be achieved without the use of an auxiliary cooling coil.

Baniyounes et al. [32,33] investigated performance of hybrid SDEC&VCS both in theory and by experiments at Central Queensland University (Rockhampton, Australia). In the first step, a simulation model predicting performance of the system was developed based on TRNSYS software, and the model was adopted to quantify annual technical performance and energy saving etc. in reference to a conventional air conditioning system. Simulation results showed that the total annual cooling load was 6428 kWh. It reached its peak in the month of December and the minimum was in the month of July. Satisfied supply air could be provided by

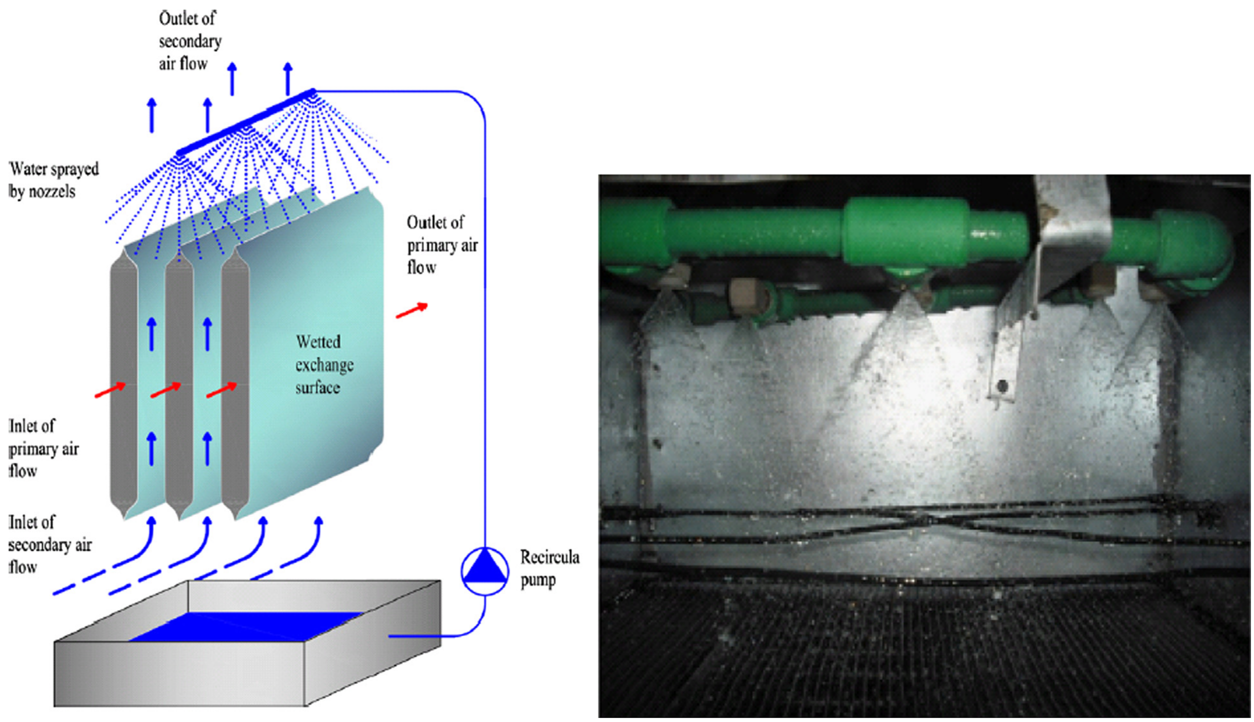

Fig. 11. Packaged wet heat exchanger used for indirect cooling process [31].

Fig. 12. Photo of hybrid solar desiccant cooling system [32].

hybrid SDEC&VCS with temperature of 25–27 °C and relative humidity ratio of near 60%. Also, it was found that area of solar collector affected COP_{th} significantly: when the area was less than 20 m^2, COP_{th} kept increasing with the increase of solar collector area; however, COP_{th} barely changed after installing more than 20 m^2 of solar collector, and the highest COP_{th} was about 1.2. Based on these theoretical analyses, an experimental setup as shown in Fig. 12 was constructed, which consists of 10 m^2 of collector's area. Annual operation experiment from November 2011 to October 2012 was conducted to analyze performance of the system. It was found that experimental results agree well with simulated ones, the actual desiccant cooling system was able to deliver treated air with conditions close enough to comfort standards. Furthermore, the system obtained annual $COP_{tot,hs}$ was 0.5 measured and 0.52 simulated, and achieved an annual SF of 0.25 measured and 0.21 simulated. Therefore, both experimental and simulated results of the Central Queensland University hybrid solar cooling system showed that the technology is promising and is effective even in the tropics.

Fong et al. [34] applied hybrid SDEC&VCS to conditioned space with high latent cooling load in Hong Kong, such as Chinese restaurant and wet market. Simulation model in TRNSYS was built up to study system performance in terms of COP and energy-saving efficiency. Designed latent and sensible loads for the Chinese restaurant and wet market are 13kW, 19 kW and 13 kW, 27 kW, respectively. Results demonstrated that hybrid SDEC&VCS could maintain indoor temperature as well as humidity ratio much more steadily compared with conventional VC system through different loading and climatic conditions within a year. Also, when designed zone humidity was constant at 60% RH, hybrid system could obtain annual saving of primary energy consumption of 49.5% for the Chinese restaurant and of 13.3% for the wet market. Meanwhile, this energy saving ratio decreased with the increasing of designed indoor humidity ratio, however, too high humidity ratio caused uncomfortable thermal environment in such places. Consequently, such hybrid system was recommended in the subtropical climates like Hong Kong in which high latent cooling load is demanded.

Khalid et al. [35] built up a hybrid SDEC&VCS in Karachi, Pakistan. This system adopted two indirect evaporative coolers instead of direct evaporative cooler in process air side: one was installed before desiccant wheel to pre-cool ambient air, and another was adopted between the sensible heat exchanger and cooling coil of VCS. It was found that desiccant wheel cooling system alone could not cool supply air to comfort conditions due to high latent and sensible loads in Karachi, auxiliary VCS was required under such conditions. Also, indirect evaporative cooer resulted in decreased regeneration temperature by 15% and decreased dehumidification by only 6%, which saved thermal energy. Then, a TRNSYS simulation model was established to further analyze performance of this system in Karachi and Lahore cooling season. Four operation modes, such as with or without pre-cooling, with or without auxiliary cooling coil, were proposed and discussed. Simulation results for Lahore showed that the system was able to cool the air to comfort level without the aid of auxiliary cooling unit for 3 months out of 7 months cooling season.

Hurdogan et al. [36] also conducted research on a modified hybrid SDEC&VCS, in which three groups of air working in parallel as shown in Fig. 13. The investigated system was with 100% fresh

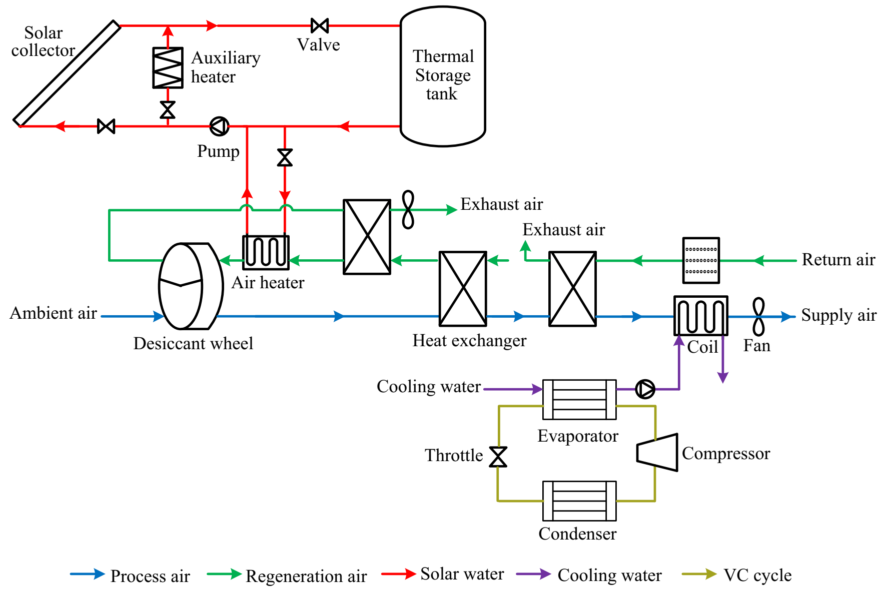

Fig. 13. Schematic figure of modified hybrid SDEC&VCS [36].

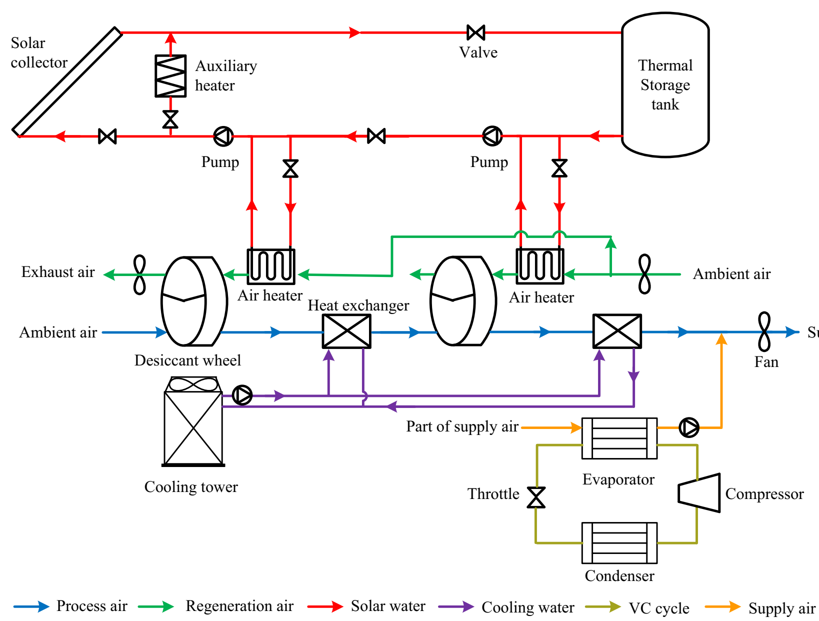

Fig. 14. Schematic figure of solar hybrid air conditioning system [37].

air, regeneration air was coming from ambient air, and return air was adopted to recover sensible heat of process air before exhausted into outdoor. Four heat exchangers were used in the system to obtain process air with low temperature and to recover heat from exhausted regeneration air. Both a simulation model and experimental setup were established by the authors, and the main aim of the research was to evaluate utilization efficiency of solar energy. It was found that solar heating system could increase regeneration temperature 5–17 °C depending on ambient dry bulb temperature and solar radiation in Adana, Turkey. Meanwhile, *SF* in regeneration heat was 45–140% and utilization of solar energy in the system increased $COP_{tot,hs}$ between 50% and120%.

La et al. [37] investigated a flat plate solar collector powered hybrid air conditioning system integrating two-stage desiccant cooling and air-source vapor compression system in parallel as shown in Fig. 14. In the system, supply air was constituted by two groups: one group from ambient air is dehumidified by TSDCS, and another one is cooled by VCS. In other words, solar powered TSDCS is adopted to remove latent load, and conventional VCS is utilized to remove sensible load. Experimental performance of such system powered by 72 m^2 solar collector was examined under Chinese local summer condition. When the ambient air possessed an average temperature of 34.6 °C and humidity ratio of 21.54 g/kg, solar radiant intensity fluctuated between 122.2 W/m^2 and 539.9 W/m^2 and average efficiency of the solar collector was 0.32, experimental results showed that for the solar TSDCS: it could achieve an average cooling capacity 10.9 kW, with corresponding average thermal COP_{th} and electric COP_{el} reaching 1.24 and 11.48, respectively; for the integrated hybrid system: 35.7% of the cooling output was contributed by solar TSDC unit, and electrical COP of whole system was 4.41 which was about 35% higher than conventional VCS. Also, a simulation model based on TRNSYS was developed to predict the performance of this hybrid system under different climate conditions. It was found that the system was

feasible in humid (Shanghai), temperate (Beijing) and extreme humid (Hong Kong) weather conditions, and seasonal electrical saving rates were from 22% to 34%.

3.3. Research progress on other hybrid SDECS

Except for conventional VCS, SDECS also can be integrated with other types of refrigeration system such as radiant cooling, absorption chiller and PVT powered refrigeration system.

Radiant cooling technology can be driven by chilled water with higher temperature, which results in high energy efficiency. However, such systems can not realize the purpose of removing latent load. Desiccant cooling technology provides a good alternative to this problem. Therefore, several researchers combined solar desiccant cooling system with radiant cooling to produce the required cooling power.

Jose et al. [38] analyzed performance of hybrid SDEC&VCS and radiant floor system as shown in Fig. 15. Performance of the system was modeled and analyzed in TRNSYS 16. It was assumed that the radiant floor within the room kept surface temperature of the floor at 2 °C higher than the wet bulb temperature of conditioned space, and hybrid SDEC&VCS was adopted to handle the odd sensible load and latent load. Performance and control strategy of the system under two climatic conditions in Spain

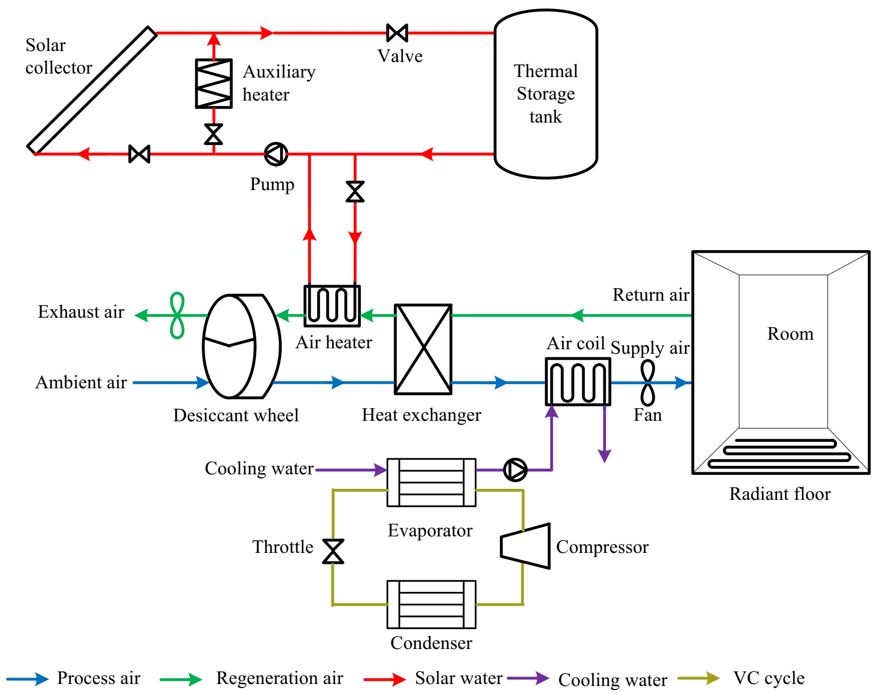

Fig. 15. Hybrid SDEC&VCS and radiant floor system [38].

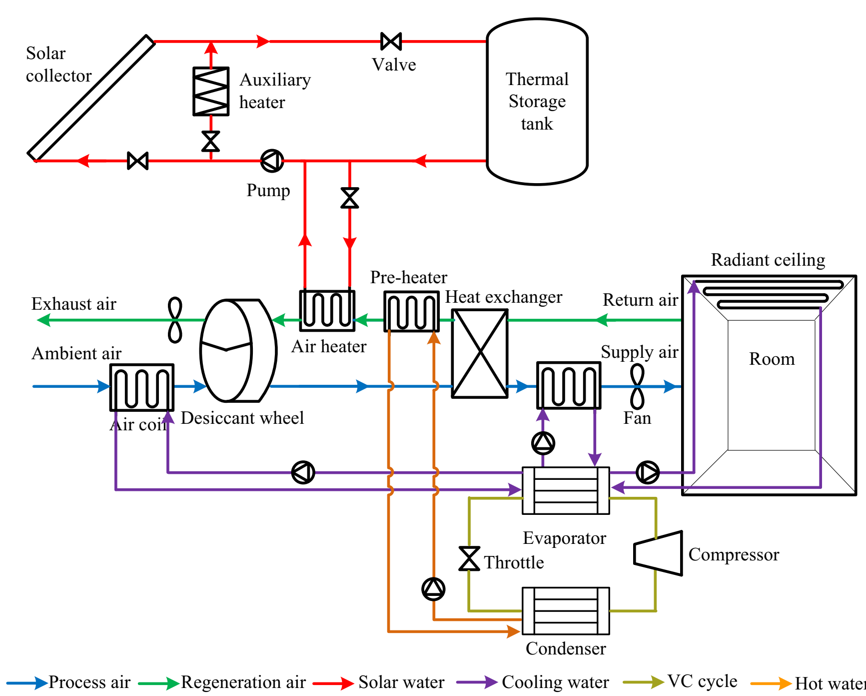

Fig. 16. Hybrid SDEC&VCS and radiant ceiling system [39].

Table 2
Summary of performance of hybrid solar rotary desiccant wheel cooling system.

Ref.	Solar subsystem	Hybrid subsystem	Overall system performance	
[29] [30]	Type: flat plate water collector Auxiliary heater: Mode 2	Type of desiccant cooling: DECS Type of refrigeration system: VCS Desiccant material: silica gel Rotation speed: 10 *r/h*	Oslo, Norway (simulation)	$T_{amb} \approx 19–28\ ^{\circ}C$ $d_{amb} \approx 11.3\ g/kg$ $T_{reg} \approx 91.8\ ^{\circ}C$ $T_{sup} \approx 18\ ^{\circ}C$ *Gas saved:* 93%
			London, UK (simulation)	$T_{amb} \approx 20–29\ ^{\circ}C$ $d_{amb} \approx 11.0\ g/kg$ $T_{reg} \approx 86.7\ ^{\circ}C$ $T_{sup} \approx 18\ ^{\circ}C$ *Gas saved:* 25.1%
			Budapest, Hungary (simulation)	$T_{amb} \approx 23–34\ ^{\circ}C$ $d_{amb} \approx 11.6\ g/kg$ $T_{reg} \approx 90.9\ ^{\circ}C$ $T_{sup} \approx 18\ ^{\circ}C$ *Gas saved:* 33.9%
			Lyon, France (simulation)	$T_{amb} \approx 22–34\ ^{\circ}C$ $d_{amb} \approx 11.6\ g/kg$ $T_{reg} \approx 90.9\ ^{\circ}C$ $T_{sup} \approx 18\ ^{\circ}C$ *Gas saved:* 39.7%
			Sofia, Bulgaria (simulation)	$T_{amb} \approx 22–37\ ^{\circ}C$ $d_{amb} \approx 13.4\ g/kg$ $T_{reg} \approx 91.1\ ^{\circ}C$ $T_{sup} \approx 18\ ^{\circ}C$ *Gas saved:* 29.1%
			Lisbon, Portugal (simulation)	$T_{amb} \approx 26–36\ ^{\circ}C$ $d_{amb} \approx 11.9\ g/kg$ $T_{reg} \approx 93.7\ ^{\circ}C$ $T_{sup} \approx 18\ ^{\circ}C$ *Gas saved:* 38.5%
			Athens, Greece (simulation)	$T_{amb} \approx 30–39\ ^{\circ}C$ $d_{amb} \approx 11.9\ g/kg$ $T_{reg} \approx 91.9\ ^{\circ}C$ $T_{sup} \approx 18\ ^{\circ}C$ *Gas saved:* 46.5%
[31]	Type: flat plate water collector Area: 22.6 m^2 Volume of tank: 0.65 m^3 Auxiliary heater: Mode 2	Type of desiccant cooling: DECS Type of refrigeration system: VCS (wet heat exchanger) Desiccant material: silica gel Diameter of desiccant wheel: 700 *mm* Width of desiccant wheel: 200 *mm* Rotation speed: 15 *r/h*	Palermo, Italy (experiment)	$T_{amb} \approx 24–28\ ^{\circ}C$ $d_{amb} \approx 12–16\ g/kg$ $T_{sup} \approx 21–22\ ^{\circ}C$ $d_{sup} \approx 10.5 g/kg$ $COP_{th,dec} = 1.1$ $COP_{th,sol,dec} = 1.8$
[32]	Type: flat plate water collector	Type of desiccant cooling: DECS	Rockhampton, Australia (simulation & experiment)	$T_{amb} = 22–39\ ^{\circ}C$ (Summer) $T_{amb} = 6–28\ ^{\circ}C$ (Winter) $RH_{amb} = 45–99\%$ (Summer) $RH_{amb} = 25–70\%$ (Winter) $T_{sup} = 24–26\ ^{\circ}C$ (Summer) $T_{sup} = 26–28\ ^{\circ}C$ (Winter) $RH_{sup} = 45–60\%$ (Summer) $RH_{sup} = 50–60\%$ (Winter) $COP_{tot,hs} = 0.25–0.73$ $SF_{tot} = 0.05–0.5$ $E_{save} = 8–45\%$
[33]	Area: 10m^2 Volume of tank: 0.4 m^3 Auxiliary heater: Mode 1	Type of refrigeration system: VCS Desiccant material: silica gel Rotation speed:42 *r/h*		
[34]	Type: evacuated tubes water collector Area: 100 m^2 Volume of tank: 5 m^3	Type of desiccant cooling: DECS Type of refrigeration system: VCS Desiccant material: silica gel Diameter of desiccant wheel: 1400/1200 *mm* Width of desiccant wheel: 200 *mm* Rotation speed: 9,10 *r/h* Cooling power of VCS: 40,45 *kW*	Hong Kong, China (simulation) Conditioned space: $14 \times 14 \times 3.6\ m^3$	Monthly operation results: $T_{reg,max} = 115\ ^{\circ}C$ Chinese restaurant: $T_{ind} = 22\ ^{\circ}C$ $d_{ind} = 8.3–9.5\ g/kg$ Wet market: $T_{ind} = 24\ ^{\circ}C$ $d_{ind} = 9.2–10.4\ g/kg$ Annually averaged results: Chinese restaurant: $T_{ind} = 22.2\ ^{\circ}C$ $RH_{ind} = 56.2\%$ $COP_{th,dec} = 0.63$ $COP^{*}_{el,vc} = 3.39$ $SF = 0.295$ $PE_{save} = 49.5\%$ Wet market: $T_{ind} = 23.9\ ^{\circ}C$

Table 2 (*continued*)

Ref.	Solar subsystem	Hybrid subsystem	Overall system performance	
	Auxiliary heater: Mode 1			RH_{ind}=54.3% $COP_{th,dec}$=0.56 $COP^{*}_{el,vc}$=3.17 SF=0.286 PE_{save}=13.3%
[35]	Type: Solar air collector Area: 12 m^2 Auxiliary heater: No	Type of desiccant cooling: DECS Type of refrigeration system: VCS	Karachi, Pakistan (experiment, simulation)	Karachi: T_{amb}=29.7–32.2 °C d_{amb}=15.7–21.5 g/kg typical condition: T_{sup}=20 °C d_{sup}=7.6 g/kg $COP_{tot,pe,hs}$=0.4–0.5
[36]	Type: flat plate water collector Auxiliary heater: Mode 2	Type of desiccant cooling: DECS Type of refrigeration system: VCS	Adana, Turkey (experiment)	$T_{amb}\approx$ 29–33 °C SF=45–140% $COP_{tot,hs}\approx$ 1.0
[37]	Type: flat plate water collector Area: 72 m^2 Outlet water temperature: 60–70 °C Efficiency: 0.32 Auxiliary heater: No	Type of desiccant cooling: two-stage DECS Type of refrigeration system: VCS Desiccant material: composite silica gel and lithium chloride Diameter of desiccant wheel: 440 mm Width of desiccant wheel: 100 mm Cooling power of VCS: 20 kW	Location Shanghai, China (experiment) Beijing, China (simulation) Hong Kong, China (simulation)	Performance indicators $Q_{pc,dec}$=10.9 kW $COP_{th,dec}$=1.24 $COP_{el,vc}$=11.48 $Q_{ic,vc}$=19.6 kW $COP^{*}_{el,vc}$=3.28 $COP_{el,hs}$=4.41 Δd=7.4g/kg $Q_{pc,dec}$=8.3 kW $COP_{th,dec}$=0.95 E_{save}=31% Δd=7.7g/kg $Q_{pc,dec}$=7.6 kW $COP_{th,dec}$=0.87 E_{save}=22%
[38]	Type: flat plate water collector Area: 500 m^2 Auxiliary heater: Mode 1	Type of desiccant cooling: DECS Type of refrigeration system: VCS and radiant floor Desiccant material: silica gel	Malaga, Madrid, Spain (simulation) conditioned space: 4080 m^2	Malaga: $T_{amb}\approx$ 22–33 °C $d_{amb}\approx$ 12.7 g/kg $T_{reg}\approx$ 54.8 °C $T_{sup}\approx$ 22–26 °C Δd_{amb}=7–12.7 g/kg Madrid: $T_{amb}\approx$ 22–33 °C $d_{amb}\approx$ 6.5–8.0 g/kg $T_{reg}\approx$ 55.9 °C $T_{sup}\approx$ 20–26 °C Δd_{amb}=7–8.5 g/kg
[39]	Type: flat plate water collector Area: 22.5 m^2 Volume of tank: 0.65 m^3 Efficiency: 0.39 Auxiliary heater: Mode 2	Type of desiccant cooling: DECS Type of refrigeration system: VCS and radiant ceiling Desiccant material: silica gel Diameter of desiccant wheel: 700 mm Width of desiccant wheel: 200 mm Rotation speed:15 r/h Process/regeneration air flow ratio:3/2 Cooling power of VCS: 24.3 kW COP of VCS rated:3.47	Palermo, Italy (experiment)	Typical summer day (26 June 2009): $T_{amb}\approx$ 28–33 °C $d_{amb}\approx$ 12–16 g/kg $T_{reg}\approx$ 45–60 °C $T_{sup}\approx$ 24–26 °C $d_{sup}\approx$ 8–12 g/kg $COP_{sol,dec}$=0.67 $COP_{th,dec}$=0.53 $COP_{el,hs}$=1.94 Seasonal data (June–September): SF =44% Typical winter day (19 January 2010): $T_{amb}\approx$ 8–13 °C $T_{sup}\approx$ 16–20 °C $COP_{el,hs}$=6 SF=0.3 Seasonal data (Dec.2009–Feb.2010): SF=0.44
[40]	Type: flat plate water collector Area: 500 m^2 Auxiliary heater: Mode 2	Type of desiccant cooling: DECS Type of refrigeration system: absorption chiller and radiant ceiling Desiccant material: silica gel Diameter of desiccant wheel: 600 mm Width of desiccant wheel: 200 mm Rotation speed: 13 r/h Process/regeneration air flow ratio:0.5	Hong Kong, China (simulation) office floor area:196 m^2	annual operation with passive chilled beams (PCB): $T_{sup}\approx$ 25–25.9 °C RH_{sup}=45–60% SF=0.51 PE=38761kWh COP=0.867 (absorption chiller) annual operation with active chilled

Table 2 (*continued*)

Ref.	Solar subsystem	Hybrid subsystem	Overall system performance	
		Absorption chiller: adsorbate and adsorbent: LiBr-H_2O Cooling power: 26 kW		beams (ACB): $T_{sup} \approx 24.8–25.4\ ^\circ C$ $RH_{sup}=45–55\%$ $SF=0.459$ $PE=38408kWh$ $COP=0.858$(absorption chiller)
[41]	Type: single glazed solar air collector and PV Area: 10–50 m^2 (0–100% solar air collector or PV) Efficiency of air collector: 0.4–0.75 Thermal efficiency of PV: 0.05–0.4 Auxiliary heater: Mode 2	Type of desiccant cooling: DECS Type of refrigeration system: VCS Flux ratio of process to regeneration air: 1:1	Palermo, Italy (simulation) Conditioned space:107 $m^2$451 m^2 Office: 10 persons Lecture room: 60 persons	$T_{amb} \approx 15–35.7\ ^\circ C$ $d_{amb} \approx 10–24 g/kg$ For office operation: energy saving ratio: 50–90% $SF=55–80\%$ (cooling) $SF=65–85\%$ (heating) For lecture room operation: energy saving ratio: 50–90% $SF=65–80\%$ (cooling) $SF=80–95\%$ (heating)
[42]	Type: evacuated tube water collector Area: 100 m^2 Volume of tank: 5 m^3	Type of desiccant cooling: DECS Type of refrigeration system: NO Diameter of desiccant wheel: 2000 mm Width of desiccant wheel: 200 mm Rotation speed: 20 r/h Ratio of wheel section for regeneration:0.5	Hong Kong, China (simulation) Q_{sen}:19 kW Q_{lat}:1 kW Conditioned space: 200 m^2	Annual performance: $T_{reg}=85\ ^\circ C$ $SF=0.522$ $COP_{th,dec}=1.059$ $PE=128052\ kW$
	Type: evacuated tube water collector Area:12m^2 Volume of tank: 5 m^3	Type of desiccant cooling: DECS Type of refrigeration system: VCS (full fresh air system) Diameter of desiccant wheel: 1600 mm Width of desiccant wheel: 200 mm Rotation speed: 7 r/h Ratio of wheel section for regeneration:0.5		Annual performance: $T_{reg}=71\ ^\circ C$ $COP_{th,dec}=1.174$ $COP_{el,vc}=3.210$ $SF=0.908$ $SF_{tot}=0.768$ $PE=128052\ kW$ Monthly performance: $T_{ind}=24–25.7\ ^\circ C$ $RH_{ind}=55–57.5\%$ $COP_{th,dec}=0.2–1.65$ $SF_{tot}=0.6–1$
	Type: Gas heater and PV Area of PV: 12 m^2	Type of desiccant cooling: DECS Type of refrigeration system: PV powered VCS (full fresh air system) Diameter of desiccant wheel: 1600 mm Width of desiccant wheel: 200 mm Rotation speed: 7 r/h Ratio of wheel section for regeneration:0.5		Annual performance: $T_{reg}=71\ ^\circ C$ $COP_{th,dec}=1.196$ $COP_{el,vc}=3.550$ $SF_{tot}=0.128$ $PE=114719\ kW$ Monthly performance: $T_{ind}=24–25.5\ ^\circ C$ $RH_{ind}=55–65\%$ $SF_{tot}=0.1–0.8$ $COP_{th,dec}=0–1.3$
	Type: PVT Area of PVT: 5 m^2	Type of desiccant cooling: DECS Type of refrigeration system: PVT powered VCS (full fresh air system) Diameter of desiccant wheel: 1600 mm Width of desiccant wheel: 200 mm Rotation speed: 7 r/h Ratio of wheel section for regeneration:0.5		Annual performance: $T_{reg}=71\ ^\circ C$ $COP_{th,dec}=1.618$ $COP_{el,vc}=3.571$ $SF=0.5$ $SF_{tot}=0.494$ $PE=99141\ kW$ Monthly performance: $T_{ind}=24–25.5\ ^\circ C$ $RH_{ind}=55–57.5\%$ $SF_{tot}=0.35–0.95$ $COP_{th,dec}=0.45–1.9$
	Type: Gas heater and PV Area of PV: 12 m^2	Type of desiccant cooling: DECS Type of refrigeration system: PV powered VCS (with return air system) Diameter of desiccant wheel: 600 mm Width of desiccant wheel: 200 mm Rotation speed: 13 r/h Ratio of wheel section for regeneration:0.5		Annual performance: $T_{reg}=81\ ^\circ C$ $COP_{th,dec}=0.736$ $COP_{el,vc}=3.816$ $SF_{tot}=0.518$ $PE=49393\ kW$ Monthly performance: $T_{ind}=24–25.7\ ^\circ C$ $RH_{ind}=50–62\%$ $SF_{tot}=0.4–0.75$ $COP_{th,dec}=0.3–0.8$
	Type: PVT	Type of desiccant cooling: DECS Type of refrigeration system: PVT powered VCS (with return air system)		Annual performance: $T_{reg}=81\ ^\circ C$ $COP_{th,dec}=0.857$

Table 2 (*continued*)

Ref.	Solar subsystem	Hybrid subsystem	Overall system performance
		Diameter of desiccant wheel: 600 *mm* Width of desiccant wheel: 200 *mm* Rotation speed: 13*r/h* Ratio of wheel section for regeneration:0.5	$COP_{el,vc}$=3.817 SF=0.962 SF_{tot}=0.701 PE=53912 *kW* Monthly performance: T_{ind}=24.5–25.5 °C RH_{ind}=52.5–62% SF_{tot}=0.6–0.9 $COP_{th,dec}$=0.3–0.9
	Area of PVT: 5 m^2 Type: evacuated tube water collector Volume of tank: 5 m^3	Type of desiccant cooling: DECS Type of refrigeration system: absorption chiller (with return air system) Diameter of desiccant wheel: 600 *mm* Width of desiccant wheel: 200 *mm* Rotation speed: 13 *r/h* Ratio of wheel section for regeneration:0.5	Annual performance: T_{reg}=81 °C $COP_{th,dec}$=0.835 $COP_{el,vc}$=0.784 SF_{tot}=0.759 PE=53936 *kW* Monthly performance: T_{ind}=24.5–25.5 °C RH_{ind}=50–62% $COP_{th,dec}$=0.3–0.9 SF_{tot}=0.55–1

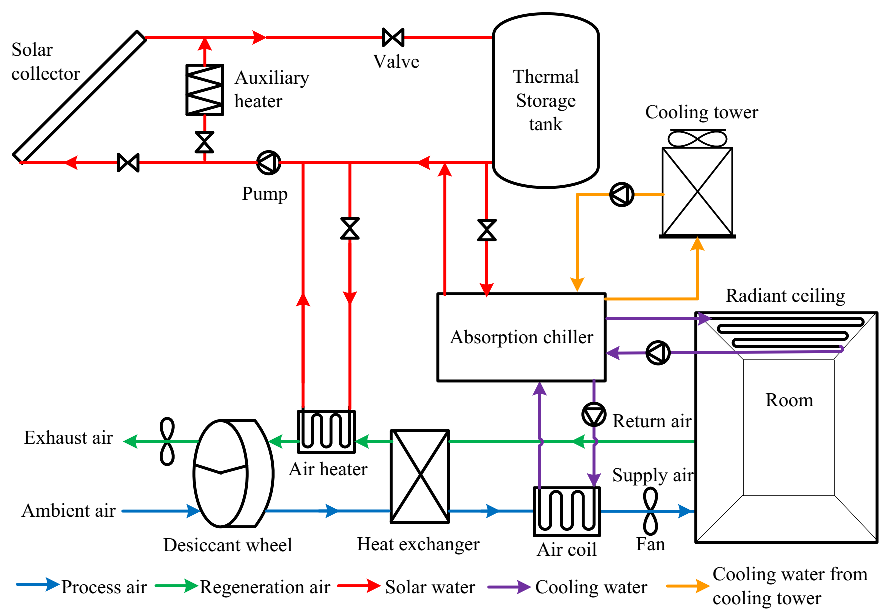

Fig. 17. Hybrid SDEC and absorption chiller system [40].

(both with hot climate, but different water content of the outside air: humid and dry) were investigated and discussed. It was found that the desiccant system was useful in hot and humid climates, and the combined system consumed 35% less electricity than the conventional one.

A modified hybrid system was built up and investigated experimentally by Beccali et al. [39] as shown in Fig. 16. In the proposed system, radiant ceiling instead of radiant floor was adopted. Meanwhile, chilled water from VCS was utilized in three ways: the first group of cooling coil was installed before desiccant wheel to pre-cool supply air, the second one was installed after sensible heat exchanger as usual to remove sensible heat, and the last one was used to provide cooling water in radiant ceiling. Also, the rejected condensation heat from chiller was adopted to preheat regeneration air before it entering solar heater. An experimental setup was established in south Italy to test actual operation performance of such system. Five control modes were proposed for system operation based on ambient temperature and humidity ratio, and a control strategy was programmed in Labview platform. Typical operation results in summer as well as in winter are summarized in Table 2. Also, it was found that the use of heat rejected by the chiller to preheat regeneration airflow allowed a reduction of the solar collector area by about 30%.

Fong et al. [40] integrated a SDECS with solar absorption chiller powered ceiling radiant cooling and investigated its performance in an office space. The zone sensible and latent loads were handled by the radiant cooling and desiccant dehumidification respectively, and absorption chiller was adopted to provide chilled water to radiant ceiling directly and to desiccant cooling system by supply air coil. Regeneration processes of both desiccant wheel cooling system and absorption chiller were driven by plate type solar collector (Fig. 17). Performance of the system was evaluated based on the year-round dynamic simulation model in TRNSYS under Hong Kong climatic condition. Also, effects of different radiant types including passive chilled beams and active chilled beams were analyzed. Main results obtained were as following: performance of the solar hybrid cooling system could meet the need of air conditioning, the primary energy saving potential of

the system could be up to 36.5% compared to conventional centralized air-conditioning system under simulation condition, and system using of passive chilled beams had better overall performances than that using of active ones.

PVT and solar air collector powered hybrid SDEC&VCS were conducted in Ref. [41]. Three different types of PVT and solar air collector driven desiccant wheel cooling system were proposed: the first one is a PVT and solar air collector powered conventional DEC&VCS (Fig. 18(a)), the second differs from the first one by use of an additional heat exchanger before desiccant wheel to recover heat from return air as shown in Fig. 18(b), and in the third configuration a heat pump was utilized both in process air for cooling and in regeneration air for heating as shown in Fig. 18(c). A comprehensive model with respect to different systems were developed in TRNSYS, both energy and economic performance of these system were analyzed for an office room as well as a lecture room with more persons under hot and humid conditions in Italy. Emphasis has to be placed on the fact that different area ratios between solar air collectors to PVT collectors were also discussed in the study. It was shown that energy saving ratio E_{save} of these systems compared to conventional VCS was in the range of 50–90%, and in most of the considered cases, the third configurations

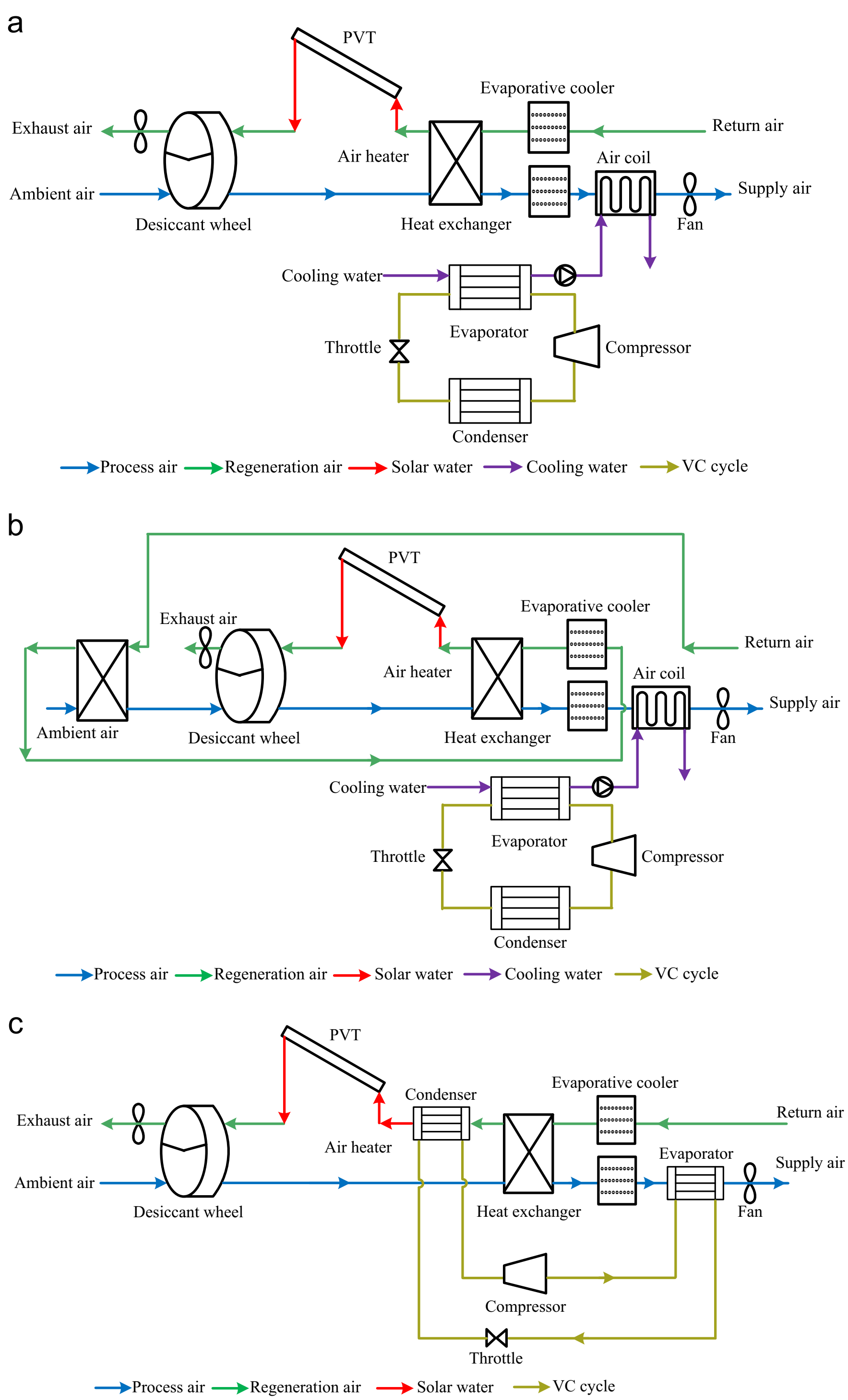

Fig. 18. (a) Basic PVT powered SDEC&VCS(b) with enthalpy recover from return air (c) with integrated heat pump [41].

demonstrated the best results in terms of primary energy saving PE_{save}. Configurations with large PVT collector area had better primary energy savings, largely due to the electricity production of the PV cells. Economics of these systems at current equipment costs and energy prices were acceptable.

In order to improve performance of SDECS in subtropical Hong Kong, Fong et al. [42] proposed six hybrid systems and evaluated their annual performance for typical office application in TRNSYS: three of them are full fresh air system combined with conventional VCS (as shown in Fig. 10), PV powered VCS (electricity produced by PV is adopted to drive VCS, auxiliary heater is adopted to power desiccant cooling) and PVT powered hybrid SDEC&VCS (electricity and thermal energy produced by PVT are adopted to drive VCS and SDECS respectively), the others are return air system combined with PV powered VCS (electricity produced by PV is adopted to drive VCS, auxiliary heater is adopted to power desiccant cooling), PVT powered hybrid SDEC&VCS (electricity and thermal energy produced by PVT are adopted to drive VCS and SDECS respectively) and absorption chiller (as similar as shown in Fig. 17). All the systems were found to be feasible and could obtain up to 35.2% saving of year-round primary energy consumption compared with conventional VCS. Among these systems, the SDECS hybridized with VCS for full fresh air design and with absorption refrigeration for return air design were recommended due to the saving potentials of both primary energy and initial cost.

4. Conclusions

Solar powered rotary desiccant cooling system has become a good alternative to conventional vapor compression system, and lots of investigations have been conducted to evaluate performance of the system. These works can be divided into two groups: separate solar rotary desiccant wheel cooling system and hybrid system. Within the first group, researches can be subdivided based on different solar collector system. And within the second group, hybrid system can be classified by whether conventional VCS is adopted.

In separate solar powered rotary desiccant wheel cooling system, flat plate or vacuum tube solar collector powered DECS based on conventional ventilation mode (Fig. 1) is the most widely investigated type [5–9,11,13,16]. Besides, some modified modes such as hybrid evaporative cooling [17] and two-stage dehumidification cycle [20] are proposed to obtain enhanced performance, and there are also several studies focusing on combining solar air collector directly with rotary desiccant wheel cooling system [21,23–27]. Researches on separate solar powered rotary desiccant wheel cooling system are mainly focusing on feasible study of such system, and it is validated that the system can be adopted in some sites in Europe [8,13,16,20,23,27], Asia [6,8,9,11,20,21,25], Australia [5,17] and Africa [7] to obtain satisfied supply air. Also, it can be seen that small part [5,9,11,17,23,24] of these work conducted in experiments, others are based on simulation method. Experimental investigations are conducted to test performance of separate solar powered rotary desiccant wheel cooling system under practical summer condition (only Ref. [5] considers winter operation), due to different climatic condition and system configuration, COP of the system also varies a lot. For the simulation investigation, performance of the system is also analyzed with respect to different locations, the obtain COP is relatively high compared with experimental data.

Solar rotary desiccant wheel cooling system has good capacity of moisture removal, whereas the sensible cooling capacity is limited by evaporative cooling, and then performance of combing this system with conventional VCS (Fig. 10) is investigated by researchers [29–37]. Also, radiant cooling [38–40], absorption chiller [40,42] and PVT system [41–42] can be adopted to link with the hybrid system to obtain improved indoor air quality and higher energy-saving ratio. The application range is enlarged for hybrid system compared with separate one due to auxiliary cooling power. Energy-saving ratio of hybrid system compared with separate VC system is an important performance index (Table 2) in related research. Practical operations are conducted in [31,32,35–37,39] and others are based on simulation, studies show this type of combination can greatly decrease primary energy consumption and is extremely suitable under extreme hot or humid environments.

Though there is already a large amount of works conducting on solar powered rotary desiccant wheel cooling system, it is still possible to make progresses especially in following aspects:

(1) Almost 80% of the reviewed work conducted the investigation based on simulation model. This is effective to obtain performance under different conditions and to analyze the feasibility in initial phase. However, solar rotary desiccant wheel air conditioning system is expected to be applied in actual building and to relieve the pressure of energy crisis, and then experimental study on demonstration is encouraged to be involved in following work. At the same time, real-time testing data can help the model to be much more accurate.
(2) Most of the work is proceed with constant structural parameters, there is rare work conducting on obtaining optimized performance and parameters with respect to different conditions. For solar rotary desiccant wheel air conditioning system, due to the whole system is consists of several subsystems, and there are still lots of component within each subsystem, it is necessary to conduct more studies on optimization study. For example, how to obtain the highest annual COP based on different parameters.
(3) For solar rotary desiccant wheel air conditioning system especially for the hybrid system, there exists different operation modes: separate desiccant cooling mode, separate VC mode, hybrid desiccant and VC mode, solar regeneration mode, auxiliary regeneration model etc. Up to now, simple control method based on temperature and humidity ratio is proposed. Much more complex and accurate control method linking to all parameters are needed especially for actual system.
(4) Due to solar energy is not steady, one of the main challenges for solar desiccant wheel air conditioning system is how to realize sustainable operation. Most of present research works concentrate on system performance analysis with available solar energy, and auxiliary heater is widely adopted method to solve intermittent problem. Solar desiccant cooling system with energy storage can provide an effective solution, and then research on this topic is highly required and promising.

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